MIMO Extension of ATSC 3.0: System Design

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***Abstract*—This paper presents and proposes the system design and features pertaining to *ATSC 3.0 MIMO Extension*. The scope is the physical layer and closely related aspects, covering technology newly specified in A/322 (physical layer protocol), A/324 (related signaling and instructions processed in broadcast gateway), and A/327 (implementation and deployment guidelines). We detail the definition and baseline clarifications, processing and procedure descriptions, signaling parameters, and configuration constraints, together with the design rationale.**

***Index Terms*—Advanced television systems committee (ATSC) 3.0, multiple-input multiple-output (MIMO), layered MIMO, layered division multiplexing (LDM), channel bonding.**

I. Introduction

MULTIPLE-INPUT multiple-output (MIMO) broadcasting is now happening: The terrestrial MIMO network is proceeding to a commercial roll-out [1]. That present moment is the culmination of a multi-year evolution that began with preliminary text [2], [3], [4] in Advanced Television Systems Committee (ATSC) 3.0 standards, exploratory trials [5], [6], [7], progressed through targeted standards amendments [8], [9], [10], [11], [12], and converged with Brazil's national standard adoption [13].

For more than a decade, broadcast MIMO remained largely a research topic and field-trial curiosity [14], [15], [16], [17], with limited traction in commercial standards and deployments [18], [19]. MIMO is a clear opportunity to amplify spectral efficiency via spatial multiplexing, by adding parallel streams without additional spectrum or time resources [20]. The cellular broadband sector pioneered MIMO installation, aided by its structural advantage: Per-terminal spatial discrimination and the availability of point-to-point feedback channels that enable adaptive precoding and beamforming [21], [22], [23]. Broadcast, by contrast, lagged adoption due to the technical challenge of universal point-to-multipoint (PTM) transmission without feedback [24], [25], together with legacy compatibility pressure and cost constraints that favored conservative evolution [26].

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A. Brazil's TV 3.0 Standardization and MIMO Deployment: Catalyst for ATSC 3.0 MIMO Extension

The immediate trigger for MIMO deployment in digital television (DTV) was Brazil's TV 3.0 project [27], [28], [29]. This national initiative's mission was to define the next-generation Brazilian DTV standard referred to as *TV 3.0* or *DTV+*, migrating discontinuously from the previous system legacies[1] without any backwards-compatibility constraint. SBTVD Forum [30] led this initiative—through a competition among candidate technology sets submitted from worldwide—while the formal standards documents are published by the Brazilian Association of Technical Standards (ABNT). The call for proposals (CfP) was issued in July 2020 [31], consisting of six divisions presenting individual requirements: Over-the-air physical layer, transport layer, audio coding, video coding, captions, and application coding.

Notably, the physical-layer requirements in this CfP made support for MIMO and layered division multiplexing (LDM) mandatory [27]. This requirement reflected Brazil's severe spectrum congestion, seeking solution through an LDM-over-MIMO cooperation: Anticipating multiplicative throughput gain from MIMO and maximal multiplexing gain from LDM [32], [33], [34], [35].

The requirement on LDM was introduced with reference to ATSC 3.0 demonstrations, the first standard to adopt LDM. LDM is a non-orthogonal multiplexing (NOM) technique based on signal superposition and is known to deliver substantial spectral-efficiency gains over orthogonal schemes such as time-division multiplexing (TDM), particularly in unequal protection (UEP) scenarios that multiplex services with different robustness targets [36], [37], [38], [39]. Previously, a joint use of LDM and scalable video coding (SVC) attracted attention since it was demonstrated to yield reliability gains exceeding 10 dB relative to conventional approaches [40], [41], [42]. With MIMO attached, the TV 3.0 project and Brazilian stakeholders held a special interest in a use case that enables single-frequency network (SFN) transmission [43] and geographic segmented localcasting (GSL) simultaneously [32], [44], [45]—that is, coordinating distributed towers to radiate an LDM superposition of a common SFN layer and a per-transmitter GSL layer.

In addition, SBTVD Forum introduced linking transmitter identification (TxID) [46], [47] with media-service operations; accordingly, TxID-over-MIMO was made mandatory in TV

[1]The previous generations known as TV 2.0 and TV 2.5 were based on Integrated Services Digital Broadcasting-Terrestrial version B (ISDB-T_B).

3.0. The CfP also initially required channel bonding (CB) [48], [49], but as requirements evolved across phases, CB was ultimately adopted as an optional technology in the specifications.

The TV 3.0 standardization proceeded with selection in three phases. Phase 1 collected proposals and proponent responses through 30 November 2020, followed by compliance checks and profile review for each candidate technology based on submitted documentation. At this stage, four physical-layer contenders applied to the contest: ATSC 3.0 (proponents: ATSC and ETRI), Advanced ISDB-T (proponent: DiBEG), 5G Broadcast/EnTV (proponents: Qualcomm, Rohde & Schwarz, and Kathrein), and DTMB-A (proponent: DTVNEL). Phase 2 comprised laboratory testing for these candidates, conducted from July 2021 to December 2021 [50].

The following test campaigns used working prototypes, i.e., transmitter/receiver sets, submitted by each proponent. In Phase 2, continuing from the Phase 1 CfP, one of the major objectives was frequency reuse-1 [51], which required candidates to support operation at carrier-to-noise ratio (C/N) below 0 dB. CB was coupled to this scenario to compensate for throughput loss. However, after the Phase 3 laboratory tests, the frequency reuse-1 target was deferred, and the focus shifted to GSL. In fact, the Phase 3 finalists were verified to operate at C/N $\leq$ 0 dB, still enabling versatile use cases. Three candidates advanced to the additional laboratory tests in Phase 3, while DTMB-A withdrew from the competition [27]. The documented report of Phase 2 results was published in [52], [53].

Phase 3 proceeded in two stages: Extra laboratory testing and on-site field testing. After the lab tests conducted from April 2023 to September 2023 (see reports in [54]), ATSC 3.0 and Advanced ISDB-T were selected as finalists and moved to the final, field stage. Located in Rio de Janeiro, Brazil, the field tests ran from December 2023 to May 2024 (see reports in [55], [56]). With viability verified on site, ATSC 3.0 was selected as the TV 3.0 physical layer. That selection was formalized in August 2025 by Presidential Decree No. 12,595, clearing the path for national engineering rollout [13].

B. Arc of the ATSC 3.0 MIMO Extension Amendment

In response to the TV 3.0 process, ATSC revised the ATSC 3.0 physical-layer specifications to add MIMO support. This revision project, called *ATSC 3.0 MIMO Extension*, was launched by a new project proposal (NPP) **N-074** [57] in March 2024. This project mainly focused on:

- Enabling the joint operation of LDM and MIMO, namely, *Layered MIMO*, and defining its system design.
- Enabling the joint operation of CB and MIMO and defining its system design.
- Defining TxID operation in MIMO systems.
- Completing the specification with the essentials required for MIMO operation.

This project principally targeted the physical-layer standard A/322 [58] and then spread beyond to the related specifications, e.g., A/324 [59] and A/327 [60]. Prior to this project, A/322's early description of MIMO, particularly referring to the edition **A/322:2024-04** [2], remained preliminary and, mostly, defaulted to single-input single-output (SISO) behavior by reference. Moreover, limited support for MIMO features conflicted with the early TV 3.0 requirements: ATSC 3.0 before *MIMO Extension* explicitly prohibited the concurrent use of MIMO with LDM and MIMO with CB, and lacked defined design for TxID over MIMO.

The revision effort proceeded in parallel with the TV 3.0 competition. In particular, the revised releases postdated the Phase 3 field tests. Despite the then-undefined standards, ATSC 3.0 proponents advanced in the competition using ETRI's system development, which satisfied all requirements. Preceding the TV 3.0 initiative, a research group at ETRI[2] had already implemented Layered MIMO and CB+MIMO (*channel-bonded MIMO*) system solutions through successive projects dating to 2017 [6]. Working prototypes were repeatedly demonstrated at global exhibitions[3] and field-verified via experimental over-the-air broadcasting.[4] These ready, field-verified implementations gave ATSC 3.0 an advantage in the TV 3.0 competition over competing proposals.

A broad set of such preparatory assets, spanning preliminary designs [15], [61], [62], prototype implementations, and lab/field verification [5], [6], expedited standardization of *ATSC 3.0 MIMO Extension* [57], allowing ATSC 3.0 to meet the TV 3.0 schedule targeting a rapid post-selection launch. The resulted investigations and experimental findings were codified into **A/322:2024-04 Amendment No. 1** [8] and **A/322:2024-09 Amendment No. 1** [9], shaping system details.[5] For example, the form of Layered MIMO Type B was formalized based on theoretic/systematic analyses in [62] and practical observations from field experiments.

The initial draft contribution for *ATSC 3.0 MIMO Extension* was made in May 2024 [63], which led to the release of the first A/322 amendment **A/322:2024-04 Amendment No. 1** and the consolidated edition **A/322:2024-09** [64] in September 2024. The second amendment with further clarifications followed in July 2025 [9], later consolidated in the 2025 roll-up edition [58]. Across this standardization path, collective contributions from various participants, feedback from the TV 3.0 Phase 1 through Phase 3 processes, and pre-launch broadcaster requirements were intensively reflected.

With the A/322 revisions in place, the studio-to-transmitter link (STL) protocol A/324 and the physical-layer recommended practice A/327 were subsequently updated to incorporate *MIMO Extension*. Beyond signal-processing operations, **A/327:2025-02 Amendment No. 1** [12] and its underlying work [35] also addressed analytical tools for deployment planning, providing a comprehensive package of solutions for MIMO-pioneering broadcasters. The latest A/327 [60] specifies a threshold C/N calculator for MIMO

[2]The authors of this paper as representatives, including authors of [5] and [6].

[3]e.g., field demos of simple MIMO and Layered MIMO Type A at *Global 8K UHD Workshop*, 2021, South Korea; Layered MIMO Type A and Type B demos at global exhibitions, including *NAB Show*, Apr. 2023, Las Vegas, NV, USA and *Global DTT Workshop*, Jul. 2023, Busan, South Korea.

[4]Tested in the network of Korea Broadcasting System (KBS), South Korea.

[5]This work builds upon the ATSC 3.0 *MIMO Extension* amendments (A/322, A/327, A/324), developed in the standardization process to which the authors contributed as system designers and drafters.

transmission, enabling geographic coverage simulation and transmitter-site planning for real-world rollouts.

Notably, *ATSC 3.0 MIMO Extension* supports both greenfield launch, e.g., a full transition as in Brazil, and incremental deployment on legacy ATSC 3.0 SISO networks, i.e., a backward-compatible soft landing for MIMO in United States, South Korea, etc. This concern is reflected in the branched design of Layered MIMO: Layered MIMO Type A targets maximal spectral efficiency, assuming MIMO-capable receivers only, whereas Layered MIMO Type B—a SISO+MIMO overlay—preserves backward compatibility. This heterogeneous overlay of Type B is new, and the concept and design can further be spread to other domains. The essence is an overlaid transmission concurrently serving receivers with heterogeneous physical capabilities. The use cases may include a combination of lightweight internet-of-things (IoT) devices and high-capacity enhanced mobile broadband (eMBB) devices, a pair of mobile/vehicular service [65], [66], [67], [68] and backhaul/inter-tower core network (ITCN) transmission [69], [70], etc. In this sense, *ATSC 3.0 MIMO Extension* could also be a historical mark in general wireless technology.

C. Scope and Organization

This paper presents and proposes the system design and features pertaining to *ATSC 3.0 MIMO Extension*. The scope is the physical layer and closely related aspects, covering technology newly specified in A/322, A/324, and A/327. We detail the definition and baseline clarifications, processing and procedure descriptions, signaling parameters, and configuration constraints, together with the design rationale.

The remainder of this paper is organized as follows. Section II reviews the related ATSC documents and release timeline. Section III refines baseline MIMO operation and terminology. Section IV establishes the concept of physical layer (PHY) functional scalability. Section V details Layered MIMO operation, Section VI describes channel-bonded MIMO. Sections VII and Section VIII discuss time-interleaving memory and service signaling for multi-PLP delivered product based on PHY functional scalability view. Section IX presents TxID over MIMO, and Section X concludes this paper.

D. Terms

Throughout this paper, the following terms are used according to the definitions in ATSC 3.0 standards.

- **LDM** – A NOM scheme that superposes multiple physical-layer signals (layers) at a specified power ratio (injection level). In ATSC 3.0, two layers are combined: One with higher power is called the *core layer (CL)*, and another with lower power is called the *enhanced layer (EL)*.
- **Physical-layer pipe (PLP)** – A structure specified to an allocated capacity and robustness that can be adjusted to broadcaster needs. A physical-layer frame consists of a bootstrap, a preamble, and one or more subframes; each subframe contains one or more PLPs.
- **Core PLP** – A PLP carried on the core layer. For single-layer (non-LDM) transmissions, the sole layer is treated as the CL; accordingly, such PLPs are also termed core PLPs.
- **Enhanced PLP** – A PLP carried on the enhanced layer.
- **Combined PLP** – A composite produced by the LDM injection stage, i.e., the overlay of the associated core and enhanced PLPs.
- **Cell** – A single complex constellation sample: A set of encoded in-phase and quadrature (I/Q) components in a constellation.

II. Related ATSC 3.0 Specification Documents and Release Timeline

ATSC 3.0 *MIMO Extension* comprises a sequence of amendments to ATSC specifications, particularly A/322, A/324, and A/327, with direct implications for physical-layer operation. This section summarizes the related versions of their release timeline.

A. A/322 (Physical Layer Protocol)

For A/322, the relevant publications are as follows. The entries below are ordered from most recent to oldest.

† **A/322:2026-01** [58] (Release: 26 January 2026)

Latest consolidated edition as of this writing; incorporates the changes from **A/322:2024-09 Amendment No. 1** and **A/322:2024-04 Amendment No. 1**.

† **A/322:2024-09 Amendment No. 1, "ATSC 3.0 Errata"** [9] (Release: 28 July 2025)

Clarifications, supplemental definitions, and corrections applied to the **A/322:2024-09** edition. Hereafter referred to as **A/322 Amd-2**, highlighting that it is the 2$^{\text{nd}}$ A/322 amendment dedicated to *MIMO Extension*.

† **A/322:2024-09** [64] (Release: 13 September 2024)

First A/322 base edition that includes the *MIMO Extension* content via incorporation of the amendment **A/322:2024-04 Amendment No. 1**.

† **A/322:2024-04 Amendment No. 1, "MIMO Extension"** [8] (Release: 13 September 2024)

Introduces the definitions, system design, signaling, etc., for *MIMO Extension*. Applied to the **A/322:2024-04** edition. Hereafter referred to as **A/322 Amd-1**, highlighting that it is the 1$^{\text{st}}$ A/322 amendment dedicated to *MIMO Extension*.

† **A/322:2024-04** [2] (Release: 3 April 2024)

Base text immediately preceding *MIMO Extension*.

B. A/324 (Scheduler/Studio to Transmitter Link)

For A/324, the relevant publications are:

† **A/324:2025-01** [59] (Release: 8 January 2025)

Latest consolidated edition; incorporates the changes from **A/324:2024-04 Amendment No. 1**.

† **A/324:2024-04 Amendment No. 1, "MIMO, LDM, CB Joint Operation"** [10] (Release: 8 January 2025)

Introduces the definitions and descriptions related to *MIMO Extension*. Applied to the **A/324:2024-04** edition. Hereafter referred to as **A/324 Amd**.

† **A/324:2024-04** [3] (Release: 3 April 2024)

Base text immediately preceding *MIMO Extension*.

C. A/327 (Guidelines for the Physical Layer Protocol)

For A/327, the relevant publications are:

† **A/327:2025-06** [60] (Release: 26 June 2025)

Latest consolidated edition as of this writing; incorporates the changes from **A/327:2025-02 Amendment No. 1** and **A/327:2024-04 Amendment No. 1**.

† **A/327:2025-02 Amendment No. 1, "MIMO System Performance Estimation"** [12] (Release: 26 June 2025)

Adds detailed explanations and guidance for MIMO operation; adds computable procedures for estimating signal-to-noise ratio (SNR) thresholds for (layered and non-layered) MIMO systems. Applied to the **A/327:2025-02** edition. Hereafter referred to as **A/327 Amd-2**.

† **A/327:2025-02** [71] (Release: 24 February 2025)

Update to **A/327:2024-12**; adds TxID code assignments; independent of *MIMO Extension*.

† **A/327:2024-12** [72] (Release: 3 December 2024)

Intermediate edition that includes the content added by **A/327:2024-04 Amendment No. 1**.

† **A/327:2024-04 Amendment No. 1, "SISO Operation of MIMO-Capable Transmitters"** [11] (Release: 3 December 2024)

Introduces the SISO operation at MIMO transmitters in the context of *MIMO Extension*. Applied to **A/327:2024-04** edition. Hereafter abbreviated as **A/327 Amd-1**.

† **A/327:2024-04** [4] (Release: 3 April 2024)

Base text immediately preceding *MIMO Extension*.

III. Description Refinement of Basic MIMO Operation

Primarily, the amendment introduces normative definitions for previously unspecified essentials and resolves ambiguities in the standard. Since ATSC 3.0 MIMO had not yet seen real-world deployment, some fundamentals remained underspecified. To enable imminent implementation and deployment, *MIMO Extension* supplies the necessary normative precision and design detail.

A. Terminology Definitions

The clarification begins by defining the term *MIMO*. A concise definition is newly added to **A/322:2024-09** [64] (via **A/322 Amd-1**) as follows. For consistency across documents that cover aspects of the ATSC 3.0 physical layer, the same terminology is also introduced in **A/324:2025-01** [59] (via **A/324 Amd**).

Definition 1 (MIMO) "A technique that allows a higher spectral efficiency and/or a higher transmission robustness, when compared to a SISO system, through addition of spatial diversity and multiplexing over two distinct paths between antennas at a transmitter and a receiver."

This description is specific to ATSC 3.0 MIMO broadcasting (see Annex L and O of [58]), not intended further as a generic communications-theory definition. For completeness, SISO is defined in parallel:

Definition 2 (SISO) "A transmission system configuration in which only a single path is created between a transmitting antenna and a receiving antenna (as opposed to MIMO, in which two or more paths are created between antennas)."

In more operational terms, MIMO mode is separately defined to denote whether a PLP is configured for MIMO:

Definition 3 (MIMO Mode) "A transmission mode in which a PLP is configured to create two transmitter signal paths that ultimately feed a pair of cross-polarized transmitting antennas."

For clarity, ATSC 3.0 MIMO employs dual-polarized transmission, applying spatial multiplexing across two orthogonal polarizations. This polarization-based realization is one specific instantiation of MIMO; other realizations—e.g., cellular systems using channel-adaptive precoding on co-polar antenna arrays—also fall under the generic MIMO concept. Prior to **A/322 Amd-1**, A/322 described spatially multiplexed streams and their dedicated transmission chains using the term *antenna*. This terminology is imprecise, as multiple-antenna arrangements can occur without MIMO (e.g., diversity reception), and the phrasing risks conflation with other MIMO implementations. To address this concern, the term *Polarization* is adopted to supersede the prior use of *antenna* and is defined as follows.

Definition 4 (Polarization) "The orientation of the electric field vector of a radiated electromagnetic (radio) wave with respect to the horizon as seen from the antenna, the orientation of the wave emitted from which is described. Such orientation can be fixed linear (i.e., planar) or rotating with time (i.e., circular)."

Again, combined operation of LDM and MIMO is a notable feature introduced by **A/322 Amd-1**, with the procedure specified in Annex O of A/322. This is referred to by the shorthand defined below.

Definition 5 (Layered MIMO) "The combination of LDM and MIMO."

More precisely, ATSC 3.0 defines two types of Layered MIMO:

Definition 6 (Layered MIMO Type A) "A mode of operation in which MIMO and LDM both are active and MIMO is applied to both the CL and EL."

and

Definition 7 (Layered MIMO Type B) "A mode of operation in which MIMO and LDM both are active and MIMO is applied only to the EL, meaning that the associated CL operates in a SISO configuration."

Briefly, Layered MIMO Type A mandates MIMO-capable receivers, whereas Layered MIMO Type B retains backward compatibility with SISO receivers while also supporting MIMO receivers. The system structure and operations are detailed in Section V.

Additionally, the following concept is defined to ensure system compatibility:

Definition 8 (PHY Functional Scalability) "An attribute pertaining to SISO, MIMO, CB, and their combined operations, describing the hierarchical compatibility among these technology sets."

which is detailed in Section IV.

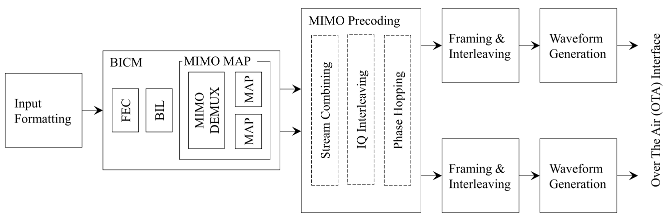

Fig. 1. Block digram of baseline MIMO operation.

B. Definitions for System Operation and Extended Features

This section turns to system operation, focusing on the baseline MIMO mode without concurrent use of LDM or CB. Changes are discussed at a general level; specific functional extensions and design details are presented in the following sections.

1) Preliminaries: Baseline MIMO Architecture (Prior to A/322 Amd-1): As noted, the previous edition **A/322:2024-04** already specified an initial system structure for MIMO. It was limited to a baseline, stand-alone MIMO configuration, disallowing joint operation with LDM, CB, or TxID. The previous description also several details needed for deployment, which were subsequently added by **A/322 Amd-1** and **A/322 Amd-2**. Before detailing the amendments, this subsection summarizes the **A/322:2024-04** baseline, referring to the illustration in Fig. 1.

Fig. 1 depicts the processing chain that produces MIMO-modulated PLP(s). Baseband packets (BBPs) created by the input-formatting block are fed into the bit-interleaved coded modulation (BICM) block, which implements forward error correction (FEC) encoding and constellation mapping. Specifically, the FEC and bit interleaving stages are unchanged from SISO (see Sections VI-A and VI-B of [58]), whereas the subsequent constellation mapping stage is replaced by MIMO mapping in MIMO mode. In particular, the (bit-interleaved) codewords are split into two parallel bit streams at the MIMO demultiplexer, each mapped to a cell stream by its dedicated constellation mapper. Operations of the MIMO demultiplexer and the subsequent constellation mappers are collectively referred to as MIMO mapping.

The cell streams from the BICM block enter the MIMO-precoding block, which may include three optional stages: Stream combining, I/Q polarization interleaving, and phase hopping. MIMO precoding is applied to mitigate possible channel correlations via vector/phase rotations or component switching executed at each stage. The two resulting cell streams are then coupled to Polarization #1 and Polarization #2 for transmission.

Remark 1 (Identification of Polarizations #1 and #2) In ATSC 3.0, each polarization is tied to a specific cell stream. Simply, the mapping originates in the bit indices within the codeword rendered at the BICM bit interleaving stage. For the post-bit-interleaving codewords, bits are indexed in order, starting at zero. The MIMO demultiplexer maps even-indexed bits to the Polarization #1 group and odd-indexed bits to the Polarization #2 group. This grouping carries through to cells: We provisionally denote the post-MIMO-mapping cell pair by (X_{2i}, X_{2i+1}), with X_{2i} associated with Polarization #1 and X_{2i+1} with Polarization #2, where i is the pair index within the FEC block, starting at $i = 0$. MIMO precoding converts (X_{2i}, X_{2i+1}) to (S_{2i}, S_{2i+1}) while preserving the indexing rule. S_{2i} herein are the actual cells to be transmitted on Polarization #1, and S_{2i+1} are those to be transmitted on Polarization #2. ■

The framing-and-interleaving block and the waveform-generation block are applied per Polarization, processing the post-precoding cells in parallel. These functions basically follow those specified for SISO mode, except where noted. For example, the inverse fast Fourier transform (IFFT) stage in the waveform-generation block shall be as described in Section III-B3, which differs from the SISO definition.

Note that the *MIMO Extension* amendments refer to this structure as the baseline and refine and extend it. Accordingly, in this paper, single-layer (non-LDM), non-bonded MIMO is hereafter referred to as baseline MIMO (or basic-mode MIMO) for brevity.

2) Clarifications in Overall Block Architecture: As shown in Fig. 2, *MIMO Extension* introduces two changes to the overall block diagram (in Section IV of [58]):

(i) The constellation mapper (MAP) sub-block within BICM is revised to an optional form allowing selection between MAP and MIMO MAP.

(ii) The MIMO precoding and LDM combining blocks are relocated relative to the **A/322:2024-04** edition.

The affected blocks are highlighted in red in Fig. 2. Note that the solid lines show blocks common to all configurations, dotted lines show blocks specific to LDM and dashed lines show blocks specific to MIMO.

Both changes (*i*) and (*ii*) are driven by the definition of Layered MIMO. First, (*i*) is required to allow Fig. 2 embrace the possibilities SISO LDM, Layered MIMO Type A, and Layered MIMO Type B. SISO LDM uses a MAP+MAP combination, Layered MIMO Type A uses MIMO MAP+MIMO MAP, and Layered MIMO Type B uses MAP+MIMO MAP. The optional selector in Fig. 2 accommodates these combinations.

Additionally, (*ii*) follows from the Layered MIMO structure. Before **A/322 Amd-1**, MIMO precoding and LDM combining were not permitted concurrently, so their relative ordering in the processing chain was immaterial. With joint operation now specified, the block diagram is revised accordingly.

Specifically, the relocation avoids the following issue: If LDM combining were performed before MIMO precoding, the core and enhanced PLPs are forced to share exactly the same precoding process. However, several precoding sub-processes depend on PLP-specific modulation and coding (ModCod) settings. This coupling is ill-defined and would preclude independent CL/EL configurations. Therefore, MIMO precoding must precede LDM combining.

3) Clarification in MIMO Waveform Generation (Basic Mode) and SISO Operation in MIMO Transmitters: Until **A/322 Amd-1**, MIMO was not yet under active deployment planning, and therefore the specification provided only a preliminary basis for MIMO. For instance, many functional blocks—including waveform generation—were specified simply to follow the SISO-mode definitions. However, the SISO IFFT description itself is incompatible with MIMO configurations because it neither identifies the pairing of co-indexed

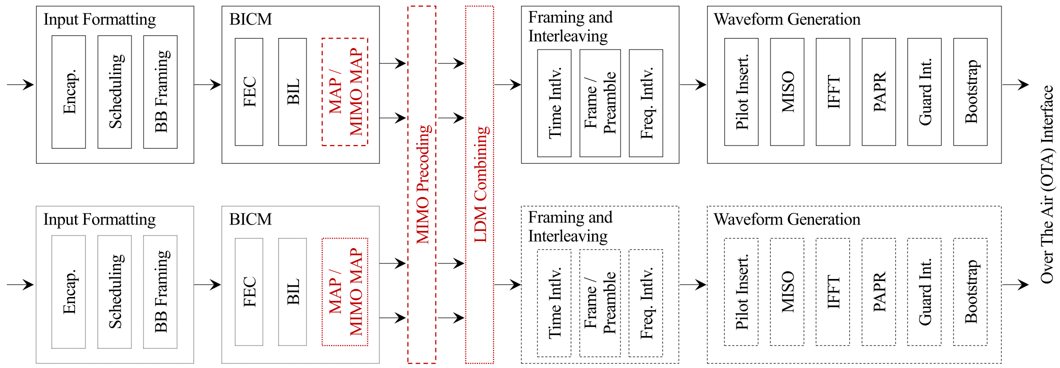

Fig. 2. Block diagram of the overall system architecture including MIMO features (revised via **A/327 Amd-1**).

cells on Polarizations #1 and #2 nor acknowledges their independence across Polarizations.

To resolve this ambiguity, we define in **A/322 Amd-1** a formula for the IFFT-output signal per Polarization as follows:

$$X_{\mathrm{IFFT}}(t;a) = \sum_{l=0}^{L_{Fp}-1} \frac{1}{\sqrt{P_{preamble,l}}} \sum_{k=0}^{NoC_{P,l}-1} c_{l,k}\psi_{l,k}(t) + \sum_{\substack{m=0,\\ m\in S_{M,a}}}^{N_{SF}-1} \frac{1}{\sqrt{P_{data,m}}} \sum_{l=0}^{L_{SFm}-1}\sum_{k=0}^{NoC_m-1} c_{a,m,l,k}\psi_{m,l,k}(t) \quad (1)$$

with notation summarized in Table I. $\psi_{l,k}(t)$ and $\psi_{m,l,k}(t)$ are the wave functions following the same definitions in Section 8.3 of [58].

The power parameters are defined as per Polarization; the index a and the parameters $c_{a,m,l,k}$ and $S_{M,a}$ are introduced. Note that (1) applies to SISO and basic-mode MIMO only.

A notable feature is $S_{M,a}$, which enables the TDM between SISO and MIMO subframes. In principle, ATSC 3.0 implicitly implied such TDM-based coexistence (via subframe-level indication of SISO/MIMO use), but a detailed, explicit description had been absent. Expression (1), with the parameter $S_{M,a}$, makes this coexistence explicit and also formalizes SISO operation at MIMO transmitters.

This aspect is tied to Polarization activation. Depending on regulation or operator policy, the Polarization used for SISO transmission may be constrained. For example, a service region may require that any SISO PLP be transmitted only on horizontal polarization, even when multiplexed with MIMO PLPs. Conversely, some other regions may allow both Polarizations to be active for SISO when the source is a MIMO transmitter and both polarizations are authorized in the radio frequency (RF) band.

To provide a fundamental, universal framework accommodating both possibilities, SISO operation at a MIMO-capable transmitter is articulated by two options:

- Option 1: Polarization #1 transmits SISO subframes; Polarization #2 is inactive during those subframes.
- Option 2: Polarizations #1 and #2 transmit identical signal copies of the SISO subframes.

TABLE I
LIST OF NOTATION

Symbol	Description
a	Polarization index. $a = 0$ and $a = 1$ indicate Polarizations #1 and #2, respectively.
k	Carrier number (index).
l	OFDM symbol number starting from 0 for the first Preamble symbol of a frame and being reset at the first OFDM symbol of each subframe.
m	Subframe number, $0 \leq m < N_{SF}$.
$c_{l,k}$	Complex modulation value for carrier k in the $(l+1)^{\text{th}}$ Preamble symbol.
$c_{a,m,l,k}$	Complex modulation value for carrier k of the OFDM symbol number l, in subframe m associated with Polarization a.
$S_{M,a}$	Set of subframe numbers, for which Polarization a is active during the corresponding transmission.
$NoC_{P,l}$	Number of carriers in the $(l+1)^{\text{th}}$ Preamble symbol. The first Preamble symbol ($l = 0$) always has the minimum NoC and the following Preamble symbols ($0 < l < L_{\mathrm{Fp}}$) share the same NoC value that is signaled in L1-Basic.
NoC_m	Number of carriers of subframe m.
$L_{\mathrm{SF}m}$	Number of data and subframe boundary symbols in subframe m.
L_{Fp}	Number of OFDM symbols in the Preamble.
N_{SF}	Number of subframes in the frame.
$P_{\mathrm{preamble},l}$	Per-Polarization frequency domain total power of $(l+1)^{\text{th}}$ Preamble symbol.
$P_{\mathrm{data},m}$	Per-Polarization frequency domain total power of each data and subframe boundary symbol in subframe m.

Option 2 is realized by constraining the constellation inputs so that, for any SISO subframe index m, $c_{0,m,l,k} = c_{1,m,l,k}$ for all valid (l, k).

Returning to TDM-based coexistence of SISO and MIMO subframes, we categorize the scenarios into two (or three) cases formalize them using $S_{M,a}$ and $c_{a,m,l,k}$.

- Case 1. Pure MIMO frame

For physical-layer frames consisting solely of baseline MIMO subframes,

$S_{M,a}$ shall consist of every integer within the range $0 \leq m < N_{SF}$, regardless of the value of a. That is, $S_{M,a} = \{0,\ldots, N_{\mathrm{SF}} - 1\}$.

- Case 2. Coexistence with SISO subframes

Once the SISO operation is selected between Options 1 and 2, it is consistently maintained over a physical-layer frame. If Option 1 is applied, $S_{M,a}$ shall be defined accordingly as follows:

$S_{M,a}$ shall be determined as follows: If $a = 0$, $S_{M,a} = \{0,..., N_{SF} - 1\}$. If $a = 1$, $S_{M,a}$ consists of the subframe numbers that use MIMO.

For example, if $N_{SF} = 4$ and only subframes $m = 2$ and $m = 3$ use MIMO, then $S_{M,1} = \{2, 3\}$ and $S_{M,0} = \{0, 1, 2, 3\}$.

If Option 2 is applied, $S_{M,a}$ and $c_{a,m,l,k}$ shall satisfy the following:

$S_{M,a}$ shall consist of every integer within the range $0 \leq m < N_{SF}$, regardless of the value of a. That is, $S_{M,a} = \{0,..., N_{SF} - 1\}$.

$c_{a,m,l,k}$ shall satisfy $c_{0,m,l,k} = c_{1,m,l,k}$, if m indicates a SISO subframe.

- Case 3. Pure SISO frame from a MIMO transmitter

One may also consider the possibility that all subframes are SISO but processed by a MIMO-capable chain. In that case, $S_{M,a}$ and $c_{a,m,l,k}$ shall be determined as:

$S_{M,a}$ shall consist of every integer within the range $0 \leq m < N_{SF}$, regardless of the value of a. That is, $S_{M,a} = \{0,..., N_{SF} - 1\}$.

$c_{a,m,l,k}$ shall satisfy $c_{0,m,l,k} = c_{1,m,l,k}$, if m indicates a SISO subframe.

Note that Case 2 gives the most general form, with Cases 1 and 3 as special cases. This concept is further generalized in Section V to encompass coexistence with Layered MIMO subframes. Note also that the *ATSC 3.0 MIMO Extension* specifications allow TDM between MIMO and SISO PLPs only at the subframe level, not within a single subframe.

4) Concepts of Extensional Technologies: In line with opening, major system concepts established by *MIMO Extension* are listed as follows. From a system-structure and functionality viewpoint, the following operations are introduced as *extensional technologies* of MIMO:

- *Layered MIMO (see Section V)* – Combination of LDM and MIMO, further specified in two types:
- *Layered MIMO Type A*: MIMO+MIMO overlay
- *Layered MIMO Type B*: SISO+MIMO overlay
  As with baseline MIMO, Layered MIMO requires the capability to process two Polarization chains.
- *Channel-bonded MIMO (see Section VI)* – Combination of CB and MIMO. This paper uses the abbreviation *channel-bonded MIMO* for brevity, whereas the ATSC 3.0 specifications typically say *MIMO with CB*.
  Channel-bonded MIMO requires the capability to process four physical-layer chains in total–two polarization chains per RF channel (two RF channels).
- *Joint use of LDM, CB, and MIMO (all-inclusive)* – Combination of LDM, CB, and MIMO. This configuration also requires four physical-layer chains– two polarization chains $\times$ two RF channels.
- *TDM coexistence of those (+SISO)* – Subframe-level TDM among subframes using different technology combinations (e.g., SISO, MIMO, Layered MIMO, channel-bonded MIMO, etc.).
- *TxID with MIMO (see Section IX)* – Operation of TxID under a MIMO topology.

In parallel, the following items are also introduced:

- *Backward-compatible L1 signaling design (see Section V)*

The corresponding L1-signaling parameters are defined accordingly to enable the above extensions. A special feature of this signaling amendment is its backward-compatible design, which enables legacy receivers unaware of *MIMO Extension* to remain compliant and operate correctly.

- *PHY functional scalability (see Section IV)*

In A/327, we establish a conceptual framework tied to receiver/transmitter capability, termed *PHY functional scalability*. This framework underpins the normative rules for time interleaving (TI) and IP-level signaling allocation described in Sections VII and VIII.

Furthermore, in A/327 via **A/327 Amd-2**, the following is also defined:

- *Estimation method for required SNR for MIMO*

Methods are provided to estimate the decoding-threshold SNR [73], [74] for MIMO signals to support network-coverage prediction, with particular attention to cross-polarization interference; the associated MIMO channel model is also developed. Details are presented in [35].

IV. PHY Functional Scalability: Coexistence of SISO, MIMO, and CB

As implied above, a single transmitter can be provisioned with multiple capabilities, including SISO, MIMO, and CB operations. Networks utilizing such transmitters may operate extensional technologies, such as MIMO and CB, while still enabling SISO operations. This yields a heterogeneous coexistence/multiplex of PLPs using different operations. In particular, a single transmitted emission, more specifically a complete delivered product (CDP), may include MIMO or channel-bonded PLPs alongside SISO PLPs. Alternatively, a CDP may consist solely of MIMO and channel-bonded PLPs while having no SISO PLPs.

This necessitates provisions that allow receivers with partial capabilities to access an appropriate subset of the CDP. For example, the allocation of low-level signaling (LLS) is designed with compatibility in mind (see Section VIII). Likewise, the L1 signaling for Layered MIMO Type B is designed to preserve backward compatibility for SISO-only receivers (see Section V). Rules governing TI memory are aligned with the same goal (See Section VII). In short, the compatibility provisions reflect physical capability constraints and enforce PHY functional scalability. Representative examples include:

- A MIMO-capable transmitter or receiver can perform all SISO operations, but a SISO-capable transmitter or receiver may not necessarily support MIMO operations.
- An entity that supports channel-bonded MIMO will also support MIMO and CB individually (and SISO as well). Conversely, support for only one of MIMO or CB does not imply support for their joint operation.

In ATSC 3.0, SISO is the mandatory baseline capability; MIMO, CB, and MIMO+CB are extensions layered on top of SISO. Entities that implement any extension must interoperate

TABLE II
PHY Functional Scalability Tiers

Tier	Technology
Tier 1 (highest priority and lowest scalability)	Pure SISO
Tier 2	MIMO, CB
Tier 3	Channel-bonded MIMO

TABLE III
Example of PHY Functional Scalability With Sub-Tiers

Tier		Technology
Tier 1		Pure SISO
Tier 2	Tier 2-1	MIMO
	Tier 2-2	CB
Tier 3		Channel-bonded MIMO

with the functional subsets required by that extension, e.g., SISO fallbacks, single-channel operation. This demonstrates the scalability among SISO and extensional technologies.

PHY functional scalability (abbreviated as PHY scalability) is defined in this context to express compatibility priority across features. PHY scalability can be organized in tiers as presented in Table II. A higher tier denotes a strict superset of capabilities: if a technology is assigned Tier N, then entities supporting it also support all technologies in Tier 1 through Tier $N-1$. In other words, a system capable of a higher-tier feature can operate in scaled-down modes at any lower tier.

Tier 1 at the ground level represents the minimum scalability and requires the highest priority for compatibility. SISO and all mandatory features belong to Tier 1. Tier 2, representing the next priority, includes MIMO and CB. Here, MIMO is understood to include Layered MIMO. In essence, MIMO and CB are considered equal in priority unless a policy preference or constraint is predefined. Where national/regional preferences exist, a tier can be further divided into sub-tiers. For example, if MIMO is deployed first and CB is introduced later, MIMO might have a higher priority than CB. In this case, the country or service region can assign MIMO and CB to Tier $2-1$ and Tier $2-2$, respectively (see example in Table III). Tier 3 is assigned to the combined operation of MIMO and CB (see Section VI). Combined operations of extensional technologies require support for the standalone subset operations and therefore occupy a higher tier than their components.

A receiver's ability to access a PLP is governed by (*i*) transmission robustness and (*ii*) PHY scalability: The receiver must meet the tier requirement of the PLP (and any applicable sub-tier policy) in addition to the robustness threshold.

V. Layered MIMO: Combination of LDM and MIMO

This section details the Layered MIMO system design, a distinguishing feature of *ATSC 3.0 MIMO Extension*. Specifically, procedures, signaling structures, and normative constraints are covered.

A. Outline

Layered MIMO is a MIMO-inclusive form of LDM transmission, whose transmit processing chain is sketched in Fig. 3.

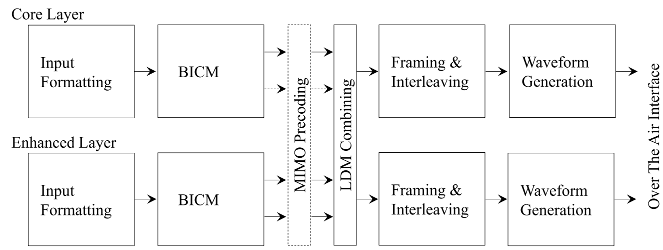

Fig. 3. Comprehensive block diagram for Layered MIMO. (Solid-line blocks) Common to all configurations; (dashed-line blocks) Can be disabled or partly applied, depending on whether the configuration is Type A or B; (solid arrows) signal flows common to all configurations; (dashed arrows) signal flows specific to Layered MIMO Type A.

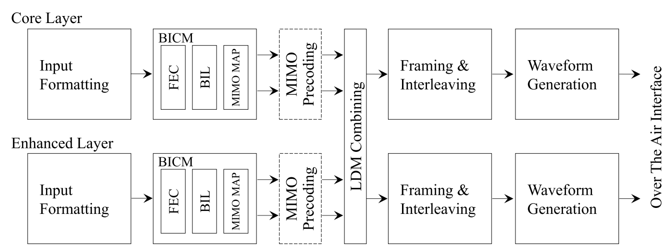

Fig. 4. Transmit processing chain for Layered MIMO Type A (Dashed-line blocks: Can be disabled or partly applied).

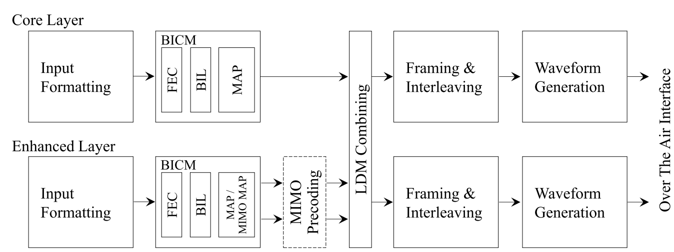

Fig. 5. Transmit processing chain for Layered MIMO Type B. (Dashed-line blocks: Can be disabled or partly applied).

That is, it is an extension of the MIMO technology described in Section III specific to multiplexing scenarios with multiple PLPs in which at least one MIMO PLP is included. This LDM+MIMO combination increases spectral efficiency by integrating two different multiplexing gains from independent domains: (*i*) LDM gain from spectrum reuse, and (*ii*) MIMO gain from spatial multiplexing.

As noted in Section III, Layered MIMO has two types:

- Layered MIMO Type A: Both core and enhanced PLPs use MIMO.
- Layered MIMO Type B: Core PLP(s) use SISO; the associated enhanced PLP(s) use MIMO.

Fig. 3 is a universal illustration that covers both types, while the type-specific structures appear in Fig. 4 and Fig. 5. Type A—a homogeneous MIMO+MIMO superposition—targets maximal throughput, whereas Type B—a heterogeneous SISO+MIMO overlay—prioritizes versatile backward compatibility within a PHY scalability context.

In particular, Layered MIMO Type B is a defining feature that presents a unique topology hitherto unseen. It is built to soft-land MIMO where ATSC 3.0 SISO is entrenched. Brazil's TV 3.0 is a greenfield case: with no legacy base, it can launch baseline MIMO and Layered MIMO Type A from the outset. By contrast, the United States and South Korea must contend with a large installed base[6] of SISO and thus cannot abruptly retire the SISO service and leap wholesale to MIMO. Type B's overlay transmission furnishes a pragmatic rollout path for MIMO in such markets. In addition, it enables efficient convergence across heterogeneous service domains, e.g., integrating SISO-based mobile broadcasting with MIMO-based ITCN transmission [39], [62].

To this end, the Type B design is deliberately engineered so that legacy ATSC 3.0 SISO receivers operate unchanged, remaining agnostic to updates in **A/322 Amd-1** and **A/322 Amd-2**, and even to the presence of MIMO signals. This constraint shapes the signal-generation process, L1 signaling topology, and other configuration rules.

This section first outlines the overall processing chains for Layered MIMO Types A and B, then specifies the functional modules that differ between them or merit remark. Subsequently, the L1 signaling design revised for *MIMO Extension* is described.

1) Layered MIMO Type A: Type A originates in the structure of [61] developed by Universitat Politècnica de València (UPV), ETRI, and Korea Maritime and Ocean University (KMOU). By analogy to the transition from single-layer SISO to LDM SISO, Type A applies LDM to baseline MIMO: Two baseline MIMO processing chains (CL and EL) are formed and then superposed.

Precisely, the transmit chain follows the procedure shown in Fig. 4. As the system comprises two layers, i.e., a core PLP and an enhanced PLP, processing begins with two parallel input-formatting blocks that generate independent BBP streams. The upper chain in Fig. 4 corresponds to CL, and the lower to EL. These BBP streams are fed into BICM blocks dedicated to each layer. Both BICM chains employ MIMO mapping; consequently, each produces two cell streams. For each layer, the two cell streams are jointly processed by the MIMO precoder. LDM combining follows, superposing the post-precoding cells by Polarization: The CL constellation symbol associated with Polarization #1 is superposed with the EL symbol associated with Polarization #1, and the same applies to Polarization #2. As a result, the LDM combining outputs two streams of combined cells, one for Polarization #1 and one for Polarization #2. The framing-and-interleaving block and the waveform-generation block are then applied per Polarization, processing these combined cells in parallel.

Unless otherwise noted, the functional blocks operate the same as which described in Section III-B.

2) Layered MIMO Type B: Layered MIMO Type B, by contrast, adopts SISO for the CL. In the current **A/322:2026-01** version specification, Layered MIMO Type B is the only standardized method to multiplex SISO and MIMO PLPs within the same subframe.[7]

[6]Pertains to both network infrastructure and distributed receivers.

[7]Otherwise, SISO and MIMO PLPs may be multiplexed across different subframes. Future revisions might perhaps define intra-subframe TDM (or frequency-division multiplexing (FDM)) for SISO+MIMO mixture, but this is not defined in the current specification.

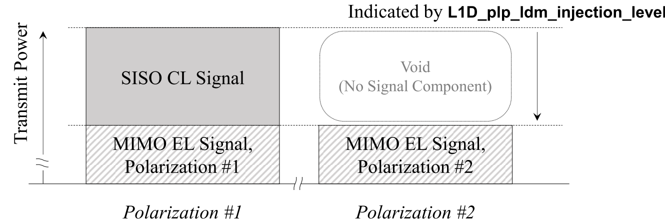

Fig. 6. Illustration for signal power allocation in Layered MIMO Type B.

Fig. 5 specializes Fig. 3 for Type B: The upper chain corresponds to the CL and the lower to the EL. In a Layered MIMO Type B system, such as shown in Fig. 5, MIMO precoding can be applied exclusively to enhanced PLPs. Therefore, unlike Section V-A1 for Type A, the BICM chain for the core PLP applies MAP rather than MIMO MAP, producing a single cell stream. As described in Section V-C, the post-BICM cells dedicated to the core PLP are recognized as mapped to Polarization #1; therefore, LDM combining applies superposition on Polarization #1 only. In line with this aspect, the transmit signal at the final stage should ultimately exhibit an asymmetric power profile as illustrated in Fig. 6. In fact, the per-Polarization power control is governed later in the waveform-generation block (see Section IV-F). In broad terms, some could see this figure as consistent with Option 1 SISO operation in Section III-B2.

Meanwhile, the enhanced PLP follows the MIMO path. Its post-precoding cells are fed to LDM combining. The LDM combining block outputs combined cells on Polarization #1 and the EL-only cells on Polarization #2. Framing-and-interleaving and waveform generation are then applied per Polarization in parallel, producing over-the-air waveforms.

Unless otherwise noted, the functional blocks operate the same as which described in Section III-B or in SISO-related sections in A/322.

B. Constellation Mapping and Precoding

Basically, Layered MIMO reuses the MIMO mapping procedure defined for baseline MIMO (Section III-B1; see Section L.4 of [58]). Likewise, for SISO PLPs in Layered MIMO Type B, the constellation mapping defined for SISO mode is reused, referring to Section VI-C of [58]. Consistent with the ATSC 3.0 LDM philosophy, each layer's BICM chain is configured independently and operates in parallel.

As outlined above, in Type A, both CL and EL apply MIMO mapping, each producing two data cell streams. In Type B, the CL BICM chain uses the SISO constellation mapper in the same stage where the EL BICM chain employs the MIMO mapper.

MIMO precoding is applied on both layers in Layered MIMO Type A and on the EL only in Layered MIMO Type B; in all cases it reuses the baseline procedure (see Section L.5 of [58]). For conciseness and ease in understanding, Type A further mandates parameter alignment between associated layers: An enhanced PLP is led to use the same I/Q polarization interleaving and phase hopping parameters as its associated core PLP(s). Precisely, if a core PLP enables I/Q polarization interleaving, the associated enhanced PLP(s) must

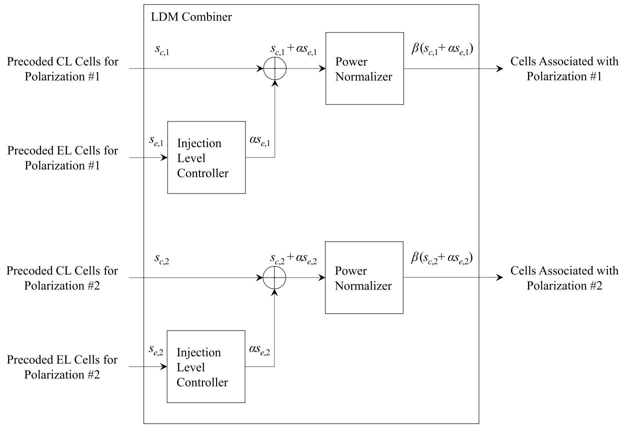

Fig. 7. LDM combining for Layered MIMO Type A.

also enable it, and vice versa. The same constraint applies to phase hopping. Stream combining is excluded from this alignment requirement.

C. LDM Combining

Layered MIMO differentiates the LDM-combining stage, but the underlying structure inherits that used in SISO mode LDM. The type-specific details are as follows.

1) Layered MIMO Type A: For Layered MIMO Type A, LDM combining is a straightforward per-polarization superposition; the processing block is shown in Fig. 7. Specifically, the CL and EL constellations associated with each Polarization are superposed. The LDM-combining block resides after MIMO precoders, so the superposition operates on post-precoding cells, regardless of whether the precoding functions are active or not.

LDM superposition is often read as *injecting* the EL into CL. The relative EL-to-CL power is hence called the *EL injection level*. The injection level, actually the absolute value of the dB-unit EL/CL power ratio, is signaled per enhanced PLP via **L1D_plp_ldm_injection_level**. For Layered MIMO Type A, both Polarizations use the same injection level; the single field **L1D_plp_ldm_injection_level** applies to Polarizations #1 and #2.

In Fig. 7, the injection level controllers power-scale the EL cells relative to their associated CL cells. Two injection level controllers—one per polarization—apply the scaling in parallel. The allowed (per-Polarization) injection level values and the resulting CL/EL power splits conform to the lookup table listed in Section VI of [58], i.e., the same table used for SISO LDM. Each output stream is normalized to unit power; the injection scaling factor α and the normalization factor β are jointly determined accordingly, depending on the injection level. Visually, Type A's LDM combining can be viewed as a per-Polarization duplication of the SISO LDM combiner.

2) Layered MIMO Type B: Layered MIMO Type B transmits the CL signal over Polarization #1 alone: i.e., the constellation-superposed signals are transmitted only on Polarization #1, while Polarization #2 carries the dedicated MIMO stream consisting solely of the enhanced PLP cells. This topology is realized as Fig. 6 and yields the LDM combining structure in Fig. 8.

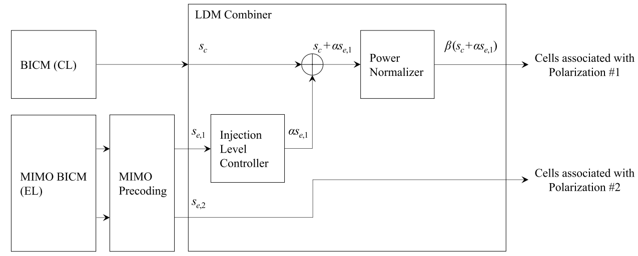

Fig. 8. LDM combining for Layered MIMO Type B.

Remark 2: (Rationale for the Layered MIMO Type B Structure): This one-sided-CL structure was selected based on theoretical analysis and empirical lab/field experiments that evaluated alternative forms. [62] provided a theoretical comparison demonstrating the optimality of the adopted architecture relative to an alternative two-sided CL option, in which identical copies of the core PLP cells are placed on both polarizations. For brevity, we denote the adopted asymmetric structure of Layered MIMO Type B as S_{L1} and the symmetric counterpart as S_{L2} (see Fig. 9). In spectral efficiency and reliability, S_{L1} demonstrated substantially higher performance than S_{L2}, as shown in Fig. 10. This observation was again verified through field experiments.

With analyses over practical aspects, [62] evidenced this by the pilot contamination issue: S_{L2} was found to be susceptible to pilot contamination, whereas S_{L1} remains robust. Note that MIMO pilot patterns place different pilot signals on Polarizations #1 and #2, as will be described in Section V-E. It should also be noticed that Polarization #1 pilot signals are identical to SISO pilots. This means that the SISO receivers, the users of the CL in Layered MIMO Type B, expect (i.e., compatible with) only Polarization #1 pilots. In practice, the real-world systems accompany cross-polarization interference (XPI) [75], causing Polarization #2 pilot signals to leak and interfere with *SISO reception*.

One should here notice that the CL and EL share the same pilot signals under the ATSC 3.0 principle. Consequently, in S_{L2} the Polarization #2 pilot signals must differ from Polarization #1 pilots even though the data cells on Polarization #2 duplicate Polarization #1. From the CL viewpoint, S_{L2} therefore transmits *interfering pilot signals* at the same power as the desired pilots, occurring critical channel estimation failures in SISO receivers. The impact could be catastrophic as Fig. 10(d), or, even from an optimistic view[8] in Fig. 10(a) – 10(c), seriously performance-degrading relative to S_{L1}. This aspect significantly harms backward compatibility with legacy SISO. By contrast, S_{L1} scales Polarization #2 pilots to the EL power. Hence, pilot interference is kept negligible, rendering S_{L1} effectively immune to pilot contamination in practice. ■

Returning to the LDM combining procedure referencing Fig. 8, constellation superposition is applied between the following two: The output of SISO BICM chain and Polarization #1 part of the output from MIMO precoder. The

[8]Fig. 10(a)–10(c) assume perfect channel state information (CSI) at the receiver but only for the *desired* channel. Because the SISO receiver is agnostic to the Polarization #2 channel, signals originating on Polarization #2 are treated as interference (may reflect the channel mismatch effect). Fig. 10(d), by contrast, employed minimum mean-square error (MMSE) channel estimation directly.

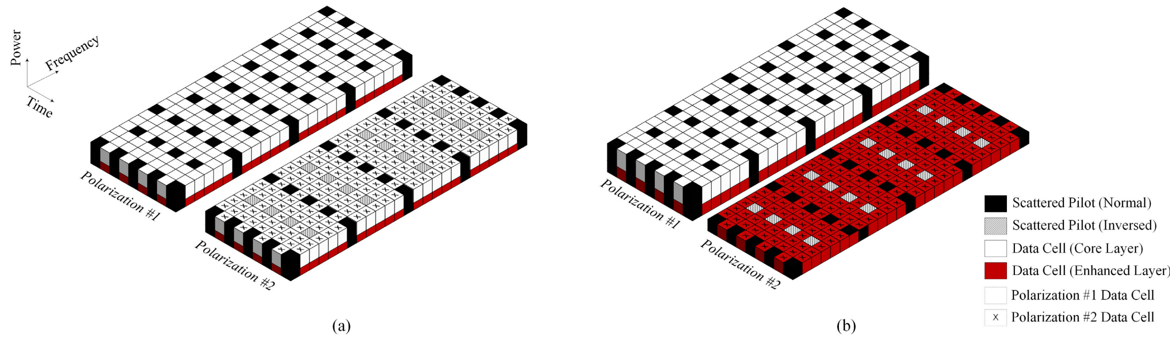

Fig. 9. Signal topology illustration: (a) Layered MIMO Type A, (b) Layered MIMO Type B (SP3_2 and MP3_2, WH encoding).

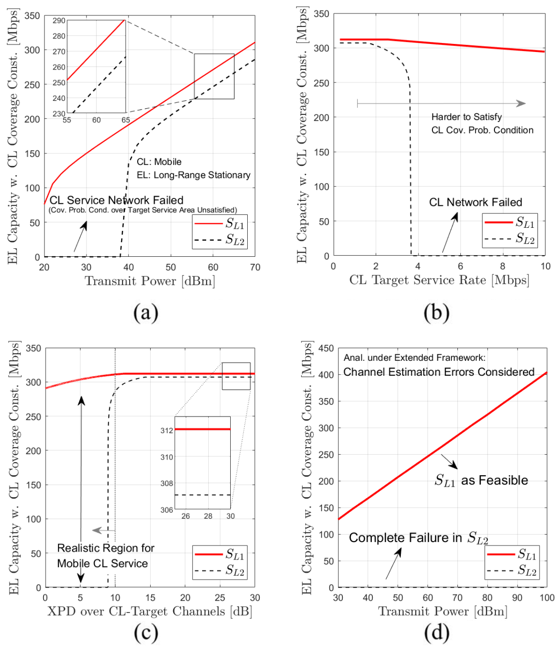

Fig. 10. S_{L1} vs. S_{L2} comparative analysis results in [62]. Addresses comprehensive spectral efficiency, in terms of the EL capacity achievable while promising the target coverage probability over a CL service area. Considers mobile service over SISO CL and long-range stationary service over MIMO EL. The injection level is optimized for each point. The effective spectral efficiency vs. (a) transmit power, (b) target service rate of CL, (c) cross-polarization discrimination (XPD) over CL service channels, (d) transmit power. (a) – (c) assume perfect CSI, whereas (d) incorporates the impact of channel estimation errors [62].

post-precoding cells associated with Polarization #2 bypass the LDM combining block transparently.

The LDM combiner therefore uses a single pair of injection level controller and power normalizer. The scaling factor α and the normalization factor β in Fig. 8 are determined by the same manner as in Type A, dependent on the injection level.

Layered MIMO Type B assigns an identical EL injection level to both Polarization streams, but the interpretation shall differ between the Polarization streams. For Layered MIMO Type B, the injection level for Polarization #1 denotes the power of EL component relative to that of the CL component, specifically confining the meaning of layer components to the Polarization #1 stream. The injection level for Polarization #2 represents the power of Polarization #2 signal relative to that of the CL component transmitted in Polarization #1.

Note that, at this stage, the Polarization #2 stream is passed through with unity power, i.e., with the same power as the LDM-superposed stream on Polarization #1. The Polarization #2 power scaling forming Fig. 6, as dictated by the injection level, is applied downstream in the IFFT stage of the waveform-generation block.

D. Framing

Before discussing framing, note that neither the bootstrap nor the preamble shall employ MIMO or Layered MIMO. That is, every data cell in a MIMO PLP or a Layered MIMO PLP shall not be allocated to any cells in preamble symbols, even if available parts remain in the last preamble symbol. In other words, the *available cells* in the last preamble symbol should not carry PLP data when the first subframe, especially when the first PLP therein, uses MIMO or Layered MIMO.

Layered MIMO frames are built in the same manner as MIMO frames. The LDM-combined cells in Layered MIMO are treated identically to cells in SISO or baseline MIMO systems. Therefore, subframes using Layered MIMO can be TDMed with other subframes using SISO or baseline MIMO. Cell multiplexing follows the same process as baseline MIMO: Data cell indexing defined for SISO is applied individually to Polarizations #1 and #2. Initialization of data cells accordingly proceeds independently for each Polarization.

Since TDM between SISO and MIMO PLPs within a subframe is disallowed as mentioned in Section III-B3, each core PLP in Layered MIMO Type B subframes shall overlap (entirely or partially) at least one enhanced PLP. Formally, in any subframe configured with Layered MIMO Type B, no core PLP can have its **L1D_plp_start** equal to or greater than the maximum value of **L1D_plp_start + L1D_plp_size** among all resent enhanced PLPs; and no core PLP can have its **L1D_plp_start + L1D_plp_size** equal to or less than the minimum **L1D_plp_start** among all present enhanced PLPs.

Meanwhile, some cell positions within a core PLP may be unassociated with any enhanced PLPs. In such cases, EL for the corresponding cell positions is filled with *enhanced layer dummy modulation values*, pseudo-randomly generated as specified.

TABLE IV
MIMO PILOT ENCODING OVERVIEW [58]

Pilot Encoding Algo.	Pol.	Scattered Pilot	Subframe Boundary Pilot	Common Cont. Pilot	Add. Cont. Pilot	Edge Pilot
WH	#1	SISO	SISO	SISO	SISO	SISO
	#2	WH	WH	SISO	SISO/WH	WH
NP	#1	NP	SISO	SISO	SISO/NP	SISO
	#2	NP	WH	SISO	SISO/NP	WH

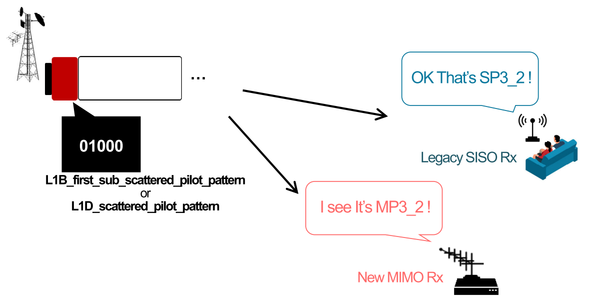

Fig. 11. Pilot interpretation in Layered MIMO Type B.

TABLE V
SIGNALING FORMAT FOR **L1B_MIMO_SCATTERED_PILOT_ENCODING** [58]

Value	Option (Syntax)
0	WH pilots or no MIMO subframes
1	Null pilots

TABLE VI
CHANGE IN STLTP **TMP()** STRUCTURE

Syntax	# of Bits	Format
Timing and Management_Packet (TMP)() {		
Structure_Data() {		
⋮		
mimo_flag	1	uimsbf
reserved	5	‘1’
}		
⋮		
Per_Transmitter_Data() {		
for (i=0; i<= # of Txs in the Tx group −1; i++) {		
tx_time_offset	16	tcimsbf
Per_Transmit_Polarization_Data() {		
for (j=0; j<=**mimo_flag**; j++) {		
xmtr_id	13	uimsbf
txid_injection_lvl	4	uimsbf
miso_filt_code_index	2	bslbf
}		
if (**mimo_flag** == 0) {		
Reserved	29	‘1’
} else {		
Reserved	10	‘1’
}		
}		
}		
}		
⋮		
}		

E. Pilot Insertion

An elegant engineering solution is introduced to realize an economical pilot-allocation scheme that maximizes signaling and structural efficiency.

Layered MIMO Type A raises no special concerns in the pilot insertion context; it can be handled identically to baseline MIMO. Note that ATSC 3.0 physical layer defines two types of encoding/patterning scheme for MIMO pilots: Walsh-Hadamard (WH) encoding and null pilot (NP) encoding. Type A Layered MIMO may use either WH or NP. In fact, as aforementioned and consistent with ATSC 3.0 LDM principles, the CL and EL share pilot signals Polarization-wise.

Special care is taken for Layered MIMO Type B to ensure PHY scalability, strict backward compatibility with ATSC 3.0 SISO. A compact solution is derived from three interesting observations:

(*i*) The WH-encoded MIMO pilot palette matches the SISO pilots on Polarization #1 exactly, as shown in Table IV.

(*ii*) A single signaling field, **L1D_scattered_pilot_pattern**, indicates the scattered pilot pattern for both SISO and MIMO. As illustrated in Fig. 11, the receiver interprets this field differently for SISO and MIMO operation, based on the expected mode and in conjunction with **L1B_mimo_scattered_pilot_encoding** value. For a given **L1D_scattered_pilot_pattern** value, pilot counts/positions are identical between SISO and MIMO; only the sequence encoding differs: e.g., SP3_2 uses the same **L1D_scattered_pilot_pattern** value as MP3_2.

(*iii*) **L1B_mimo_scattered_pilot_encoding**, which specifies the scattered pilot encoding scheme for an entire physical-layer frame, is defined as in Table V. SISO and WH-encoded MIMO pilot patterns coincide at the same value, **L1B_mimo_scattered_pilot_encoding = 0.**

From these observations, the rule is derived: For Layered MIMO Type B, WH pilot encoding is mandatory. This mandate resolves every potential conflict concisely. Moreover, this configuration aligns with the Layered MIMO Type B structure as implied by Fig. 9.

This principle effectively generalizes beyond Layered MIMO. The resulting rule is: Whenever both SISO and MIMO PLPs are present in a frame, the MIMO PLPs shall use WH pilot encoding to secure compatibility with SISO PLPs. This applies to frames containing Layered MIMO Type B subframes and to frames that alternate between SISO and MIMO subframes. In terms of L1-signaling, the condition can be detected when any **L1D_mimo_mixed** (or **L1B_first_sub_mimo_mixed**) = 1 is present, or when **L1D_mimos** and **L1B_first_sub_mimo** indicate differing SISO/MIMO modes within a frame (see Section V-H for definition). In such cases, **L1B_mimo_scattered_pilot_encoding** is set to 0, which applies uniformly to the entire portion of a single frame. As a result, all subframes in that frame shall use WH or SISO pilot encoding.

F. Multiple-Input Single-Output (MISO) Filtering: Transmit Diversity Code Filter Set (TDCFS)

ATSC 3.0 transmitters may apply intentional pre-distortion to mitigate SFN *deep nulls* caused by destructive combining in some service area. In ATSC 3.0 terminology this feature is MISO, specifically the TDCFS pre-distortion [76]. With *MIMO Extension*, TDCFS operation is also extended to be MIMO-compatible. That is, A/324 STL transport protocol (STLTP) newly defines that the TDCFS code index can be assigned per Polarization at each transmitter when MIMO is used. The data structure **Per_Transmit_Polarization_Data**() is where this definition is added, which is shown in Table VI.

In line with the pilot contamination concerns in Sections V-C2 and V-E, a sort of additional safeguard is applied in MISO: When MISO mode is enabled with Layered MIMO Type B, a MIMO transmitter assigns different TDCFS code indices to each Polarization. Concretely, within **Per_Transmit_Polarization_Data**(), STLTP sets different **miso_filt_code_index** values for Polarizations #1 and #2. This is to mitigate correlated pilot contamination at SISO receivers, which may result from cross-Polarization interference under WH pilot encoding. In effect, the Polarization #2 pilots—and their cross-polarization leakage—appear randomized with respect to Polarization #1, reducing correlated interference.

G. IFFT

The baseband waveform is, in essence, forged at the IFFT stage (see Fig. 2). Two parallel IFFT blocks generate baseband time domain signals for each Polarization stream. Below we present a generalized expression that integrates all descriptive elements, i.e., ideas in Section III-B3 are merged. With Layered MIMO included, the generalized formula for post-IFFT waveform is described per Polarization as

$$X^{LM}_{IFFT}(t;a) = \sum_{l=0}^{L_{Fp}-1} \frac{K_{S_{M,a}(0)}[a]}{\sqrt{P'_{preamble,a,l}}} \sum_{k=0}^{NoC_{P,l}-1} c_{l,k}\psi_{l,k}(t) + \sum_{\substack{m=0,\\ m\in S_{M,a}}}^{N_{SF}-1} \frac{K_m[a]}{\sqrt{P'_{data,a,m}}} \sum_{l=0}^{L_{SF_m}-1} \sum_{k=0}^{NoC_m-1} c_{a,m,l,k}\psi_{m,l,k}(t), \quad (2)$$

where:

K_m [a] is the scaling coefficient subject to subframe index m and Polarization index a. The value of K_m[a] is related to the injection level information as summarized in Table O.12.1 of [58];

$P'_{\text{preamble},a,l}$ is the frequency-domain total power of the $(l+1)^{\text{th}}$ preamble symbol for Polarization a at the IFFT input;

$P'_{\text{data},a,m}$ is the frequency-domain total power of each data and subframe boundary symbol in subframe m for Polarization a at the IFFT input;

$S_{M,a}$ is the set of subframe indices (see Table I) in which Polarization a is active. $S_{M,a}(0)$ denotes the first (minimum) element of $S_{M,a}$, i.e., the index of the first subframe activating Polarization a.

Other notations follow Table I; the pulse shapes $\psi_{l,k}(t)$ and $\psi_{m,l,k}(t)$ are as defined in Section 8.3 of [58].

Note that this stage embodies the power profile in Fig. 6. For Layered MIMO Type B, where Polarization #2 carries only the EL, the EL power on Polarization #2 is controlled

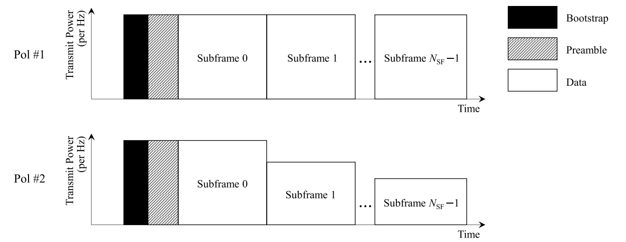

Fig. 12. An example of subframe arrangement in descending K_m [1].

here by K_m [1]. The coefficient K_m[a], computed per Table O.12.1 of [58], scales the Polarization #2 signal so that the EL power is identical across the two Polarizations. K_m[a] is defined as compatible with both Layered MIMO types, and is coupled with **L1D_plp_ldm_injection_level**.

Continued from Section III-B, subframes using Layered MIMO can be multiplexed with SISO subframes, baseline MIMO subframes, or other Layered MIMO subframes employing a different type. To make the processing explicit for SISO and non-Layered MIMO elements, we specify:

K_m [a] = 1 if subframe m is not Layered MIMO.

SISO operation options are reviewed in this context. For SISO subframes carried by a MIMO-capable transmitter, two options are defined:

- Option 1: Polarization #1 transmits SISO subframes; Polarization #2 is inactive for those subframes.
- Option 2: Polarizations #1 and #2 transmit identical copies of the SISO subframes.

Realization of $S_{M,a}$ and $c_{a,m,l,k}$ follows. With Option 1, we have

- $S_{M,0} = \{0,..., N_{\text{SF}} - 1\}$;
- $S_{M,1}$ = {indices of subframes using MIMO}.

With Option 2, we have

- $S_{M,a} = \{0,..., N_{\text{SF}} - 1\}$ for both $a \in \{0, 1\}$;
- $c_{0,m,l,k} = c_{1,m,l,k}$ if subframe m is SISO.

This presentation keeps the generalized IFFT-stage formulation (2) compact while making the SISO/MIMO coexistence, and the Layered-MIMO scaling via K_m[a], explicit.

Remark 3 (Preamble/Bootstrap Power Determination) Note that the first term in (2) represents the preamble. As indicated therein, for each Polarization the preamble symbol power is set equal to the data symbol power of the first subframe that activates that Polarization. This design shows a practical care: This aids implementation by providing a coarse power reference in the preamble that can be associated with the target PLP. However, because the preamble is non-MIMO, the CSI derived from it should not be directly transferred to MIMO (or Layered MIMO) signal decoding.

Likewise, the bootstrap symbol power is aligned in the same sense. When MIMO or Layered MIMO is used, the bootstrap symbols prefixed to a frame are identical across Polarizations, although the amplitudes may differ. For each Polarization, the bootstrap symbol amplitude matches that of the subsequent Preamble symbol—eventually matching the data symbol of the first subframe activating that Polarization.

Besides, to ease receiver gain control and to allocate the highest power to the preamble for a given subframe profile, it is specified that subframes be placed in descending order of K_m [1]. Fig. 12 illustrates an example power profile. The following explanation may further clarify SISO coexistence: SISO subframes using Option 1, i.e., Polarization #2 muted, do not define K_m [1]; this does not imply K_m [1] = 0. Therefore, such SISO subframes can precede Layered MIMO subframes. ■

Additionally, to ensure system simplicity and maintain a uniform signal level within a subframe, all enhanced PLPs in a Layered MIMO Type B subframe shall use the same injection level. That is, within a subframe using Type B, all PLPs with **L1D_plp_layer** >**0** shall be configured with the same **L1D_plp_ldm_injection_level** value.

H. Indication Topology: L1 Signaling and Interpretation

A special PHY scalability effort is made, to ensure backward compatibility while enabling all new features with minimal changes. To this end, the signaling additions are engineered so that pre-**A/322 Amd-1** devices remain agnostic and unaffected. Primarily, we reuse *reserved bit* fields (~**A/322:2024-04**) in L1-Basic and L1-Detail, which were previously undefined. Legacy receivers fielded prior to **A/322 Amd-1** do not parse these reserved areas, so the new signaling parameters are *invisible* to them and do not alter legacy operation.

Table VII shows the L1-Detail changes introduced by **A/322 Amd-1**. The highlighted region indicates newly defined fields that previously belonged to the *reserved-bit area*. L1-Basic is updated in a similar manner, although the addition is treated more cautiously due to the limited remaining bit budget. The newly defined parameters are **L1B_first_sub_mimo_mixed**, **L1D_mimo_mixed**, and **L1D_plp_mimo**.

Meantime, **L1B_first_sub_mimo** and **L1D_mimo**, which also participate in MIMO operation, are legacy fields located in the original signaling region and remain parsed by legacy SISO receivers. Accordingly, compatibility with these fields is treated carefully in the design of **L1B_first_sub_mimo_mixed** and **L1D_mimo_mixed**. At the same time, to coordinate behavior with the new parameters, the semantics of **L1B_first_sub_mimo** and **L1D_mimo** are refined appropriately. All logic is crafted to ensure that the legacy receivers continue to operate correctly while interpreting these legacy fields exactly as before.

Parameters for MIMO precoding sub-functions, such as **L1D_plp_mimo_stream_combining**, are newly placed in a previously unused signaling region, while retaining their original semantics. This placement applies opportunistically to MIMO enhanced PLPs in Layered MIMO Type B, which pretend to be invisible to the legacy systems. In the same context, **L1D_plp_mimo** is introduced to mark, within a Layered MIMO Type B subframe containing SISO and MIMO PLPs as mixed, which PLPs use MIMO and which do not.

The semantics of new parameters are as follows:

- **L1B_first_sub_mimo / L1D_mimo** – Indicates whether all PLPs in the subframe of interest use MIMO.
  ►0: At least one PLP in the subframe does not use MIMO.
  ►1: All PLPs in the subframe use MIMO.

TABLE VII
ADDITION IN L1-DETAIL SIGNALING FIELDS AND SYNTAX

Syntax	# of Bits	Format
L1_Detail_signaling() {		
⋮		
for (**i=0 .. L1B_num_subframes**) {		
if (i > 0) {		
L1D_mimo	1	uimsbf
⋮		
for (j=0 .. **L1D_num_plp**) {		
⋮		
}else {		
L1D_plp_ldm_injection_level	5	uimsbf
}		
}		
}		
L1D_bsid	16	uimsbf
for (**i=0 .. L1B_num_subframes**) {		
if (i > 0) {		
L1D_mimo_mixed	1	uimsbf
}		
if (i=0 && **L1B_first_sub_mimo_mixed**=1) || (i >0 && **L1D_mimo_mixed**=1) {		
for (j=0 .. **L1D_num_plp**) {		
L1D_plp_mimo		
if (**L1D_plp_layer**=0) {		
L1D_plp_mimo_stream_combining	1	uimsbf
L1D_plp_mimo_IQ_interleaving	1	uimsbf
L1D_plp_mimo_PH	1	uimsbf
}		
}		
}		
}		
L1D_reserved	as needed	uimsbf
L1D_crc	32	uimsbf
}		

- **L1B_first_sub_mimo_mixed / L1D_mimo_mixed** – Indicates whether the subframe of interest multiplexes MIMO and SISO PLPs.
  ► 0: At least one PLP in the subframe does not use MIMO.
  ► 1: The subframe contains only MIMO PLPs (i.e., **L1B_first_sub_mimo / L1D_mimo = 1**) or only SISO PLPs (i.e., **L1B_first_sub_mimo / L1D_mimo = 0**).

When LDM is applied within the subframe (i.e., one or more PLPs have **L1D_plp_layer** >**0**), setting **L1B_first_sub_mimo_mixed / L1D_mimo_mixed = 1** normatively implies Layered MIMO Type B: All enhanced PLPs (i.e., **L1D_plp_layer** >**0**) shall use MIMO, and all core PLPs (i.e., **L1D_plp_layer = 0**) shall use SISO.

- **L1D_plp_mimo** – Indicates, on a per-PLP basis, whether MIMO is used when the current subframe contains both MIMO and SISO PLPs. This field is signaled only if **L1B_first_sub_mimo_mixed / L1D_mimo_mixed = 1.**
  ► 0: The PLP uses SISO.
  ► 1: The PLP uses MIMO.

TABLE VIII
INDICATIONS RELATED TO MIMO

MIMO Configurations	Related L1-Signaling Assignment	
	L1B_first_sub_mimo or L1D_mimo	L1B_first_sub_mimo_mixed or L1D_mimo_mixed
All PLPs in the subframe use SISO	0	0
PLPs of both types present in the subframe	0	1
All PLPs in the subframe use MIMO	1	0
Invalid combination	1	1

The use and type of Layered MIMO are indicated per subframe via the combination of **L1D_mimo**(hereafter, shorthand for **L1B_first_sub_mimo** as well), **L1D_mimo_mixed**(hereafter, shorthand for **L1B_first_sub_mimo_mixed** as well), and **L1D_plp_layer**. The enabling of **L1D_mimo** and **L1D_mimo_mixed** is mutually exclusive (see Table VIII).

This design enables seamless PHY scalability in Layered MIMO Type B. **L1D_mimo_mixed** identifies whether the subframe contains a heterogeneous mixture of SISO and MIMO PLPs. Legacy ATSC 3.0 SISO receivers fielded before the release of **A/322 Amd-1** may be unable to parse **L1D_mimo_mixed**, since it was undefined in earlier releases. Accordingly, legacy SISO receivers can ignore the PLPs indicated by **L1D_mimo = 1.** When Layered MIMO Type B is applied, **L1D_mimo = 0** is set, so SISO receivers will proceed to decode the core PLPs encoded in SISO. By contrast, MIMO-capable receivers manufactured after the release of **A/322 Amd-1** will access the pair of indicators **L1D_mimo** and **L1D_mimo_mixed**, and hence decode MIMO enhanced PLPs even though the subframe-level flag shows **L1D_mimo = 0** for Layered MIMO Type B.

Ordinarily, the use of LDM is indicated by the presence of a nonzero **L1D_plp_layer**. However, in **A/322:2026-01**, **L1D_mimo_mixed = 1** also implies LDM, because only Layered MIMO Type B is permitted for mixed SISO/MIMO within a subframe. This means that whenever **L1D_mimo_mixed = 1** is set, the subframe shall include one or more PLPs holding **L1D_plp_layer >0.**

Again, **L1D_plp_mimo**, the per-PLP indicator of SISO/MIMO, appears when Layered MIMO Type B is used. This field is conditionally signaled only when **L1D_mimo_mixed = 1** is flagged. Consistent with the structure, PLPs in such subframes satisfy: **L1D_plp_mimo = 0** when **L1D_plp_layer = 0** and **L1D_plp_mimo = 1** when **L1D_plp_layer >0.**

VI. CHANNEL-BONDED MIMO: COMBINATION OF CB AND MIMO

Channel-bonded MIMO enables MIMO to be applied on one or both RF channels, spreading data from a single PLP across them. This combination further amplifies throughput by aggregating spectrum in addition to spatial multiplexing. Roughly speaking, CB can double the pipeline, and MIMO can double it again, yielding up to a fourfold gain. The remainder of this section describes channel-bonded MIMO in *ATSC 3.0 MIMO Extension*, as detailed in the following subsections.

A. Outline and Indication

This combination is indicated when both technology subsets, MIMO and CB, are enabled, with each signaled independently. No new flag parameters are required for this combined use. **L1D_num_rf** and **L1D_plp_num_channel_bonded** signal CB, while **L1D_mimo** (or **L1B_first_sub_mimo**), **L1D_mimo_mixed** (or **L1B_first_sub_mimo_mixed**), and **L1D_plp_mimo** signal the use of MIMO.

L1D_num_rf and **L1D_plp_num_channel_bonded** apply at the frame and PLP levels, respectively. A nonzero **L1D_num_rf** indicates that the frame contains PLP(s) using CB; the specific PLP(s) are identified by **L1D_plp_num_channel_bonded = 1.** For any PLP holding **L1D_plp_num_channel_bonded = 1** in the current RF channel, **L1D_bonded_bsid** points to the counterpart RF channel. **L1D_bonded_bsid** matches the **L1D_bsid** signaled by that counterpart RF. Broadcast stream IDs (BSIDs) are regionally unique, ensuring unambiguous pairing.

Note that ATSC 3.0 CB is described to distribute a single BBP stream across two RF channels, occupying one *pipe* in each channel. From the perspective of each RF channel, the container carrying the CB-dedicated payload is also called a PLP, while higher-layer descriptions may sometimes bind services at the PLP granularity. In this regard, the terminology can sometimes be ambiguous. For clarity, we refer to the overall construct as the *channel-bonded PLP*, and to the per-RF-channel PLPs that participate in it as *CB-participating PLPs*, *(mutually) bonded PLPs*, or *involved PLPs*, depending on the context.

A channel-bonded PLP holds an identical, unique **L1D_plp_id** across the engaged RF channels. Based on this premise, the positions of channel-bonded signals are precisely specified by tracing **L1D_plp_id** within the engaged RF channels.

As a preliminary, ATSC 3.0 CB defines two operating modes: Plain CB and SNR-averaging CB.

- Plain CB mode: Parallel transmission over two RF channels, without interaction between the chains.
- SNR-averaging mode: Cell exchange is applied between two transmission chains.

Details of the modulation chains, including the cell-exchange procedure, appear in Sections VI-B, VI-C, and VI-E.

Both CB modes remain applicable when combined with MIMO. A 2-bit field **L1D_plp_channel_bonding_format** selects the CB mode, shortly indicating whether the cell-exchange block is enabled. Behind its use, cell exchange requires tight inter-RF synchrony and PLP rate matching as prerequisites.

As long as plain CB is used, the CB-participating PLPs can use different configurations in the two RF channels, and this extends to MIMO as well. This means that bonding between MIMO and SISO is permitted. This enables cooperation between MIMO transmitters and SISO transmitters that are not

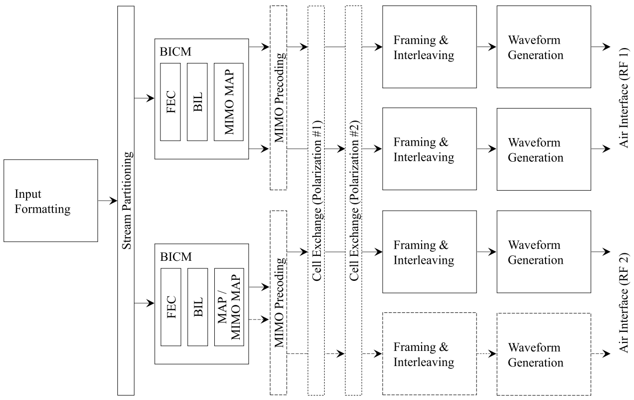

Fig. 13. Architecture illustration for channel-bonded MIMO. Dashed lines denote blocks enabled by MIMO precoding settings, and dotted lines denote blocks activated only when SNR averaging is applied.

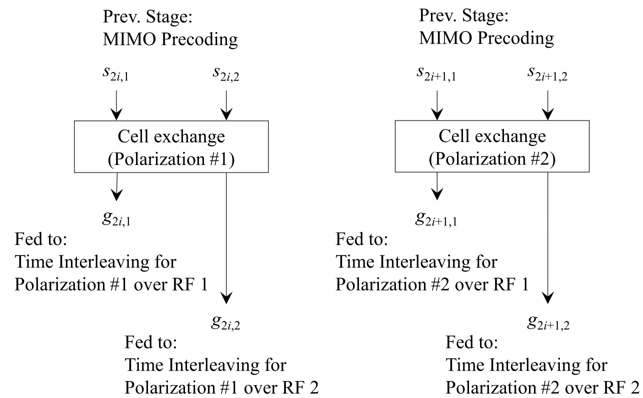

Fig. 14. Illustration of cell exchange operation.

co-located. Broadcast Gateway operation running two separate STLTP tunneled data streams (defined in Section 9.5 and Annex E of [59]) supports this type of CB. Channel-bonded MIMO is also compatible with Layered MIMO, and bonding between CL and EL signals is allowed. For example, a SISO-modulated CL in RF channel #1 may be bonded with a MIMO EL in RF channel #2. This allowance likewise covers CB between LDM and non-LDM signals.

Remark 4 (PHY Scalability Revisited) MIMO-capable transmitters can also operate in SISO mode, based on their physical capability. Thus, CB between MIMO and SISO paths allows SFNs to coordinate the following three types of transmitter sets: (*i*) A co-located transmitter unit that exclusively handles the combined operation of MIMO and CB; (*ii*) a pair of MIMO transmitters cooperating for CB, but not co-located; (*iii*) a MIMO transmitter and a SISO transmitter cooperating for CB, but not co-located. This maximizes reuse of existing transmitter/network assets and enables flexible, efficient SFN construction.

Likewise, receivers that support the combined operation of MIMO and CB are inherently capable of MIMO-only, CB-only, and SISO operation. Receivers compatible with channel-bonded MIMO, necessarily equipped with two Polarization antenna sets, can also process heterogeneous bonding between MIMO and SISO signals.

Nevertheless, such a heterogeneous form of CB is available only in the absence of the SNR averaging mode. If SNR averaging is applied, the channel-bonded PLP must maintain identical configurations across the bonded RF channels, including: BICM settings, TI settings, number of FEC blocks per subframe, multiplexing scheme, LDM layer index, use of MIMO, MIMO precoding settings, and Layered MIMO type. Consequently, whenever SNR averaging is used, both partitioned streams under channel-bonded MIMO operation apply MIMO identically; bonding occurs only within the same LDM layer; and cell exchange operates per Polarization independently.

B. Channel-Bonded MIMO Without LDM

As noted, ATSC 3.0 CB operates over two RF channels. Fig. 13 depicts the channel-bonded MIMO architecture when Layered MIMO is not used. Consistent with the CB baseline, a single input data-packet stream is partitioned into two BBP streams, each fed to the BICM chain of its respective RF channel. MIMO MAP and MIMO precoding are then applied per configuration. Cell exchange may be enabled in SNR averaging mode, as detailed later.

Again, channel-bonded MIMO is not limited to bonding between MIMO PLPs; it also permits bonding between SISO and MIMO PLPs under plain CB. In that case, the SISO PLP's BICM chain uses MAP, while the MIMO PLP in the other RF channel uses MIMO MAP. By contrast, when CB with SNR averaging is used, a MIMO PLP shall not be bonded with a SISO PLP, enabling low-complexity cell re-exchange at the receiver.

Fig. 14 abstracts the cell-exchange procedure for each Polarization. A cell exchange matrix, defined for each Polarization, shall be multiplied as follows. For each Polarization $a \in \{0,1\}$, we have the cell pair index $i = 0, 1, 2, \cdots \lfloor \frac{N_{cells}}{2} \rfloor - 1$, where N_{cells} denotes the FEC block length. Let the input cell vectors to the cell exchange block be

$$\boldsymbol{s}_i^{(0)} \triangleq \begin{bmatrix} s_{2i,1} \\ s_{2i,2} \end{bmatrix}, \quad \boldsymbol{s}_i^{(1)} \triangleq \begin{bmatrix} s_{2i+1,1} \\ s_{2i+1,2} \end{bmatrix}, \tag{3}$$

for the Polarization #1 path (even pair index $2i$) and the Polarization #2 path (odd pair index $2i+1$), respectively, where the second subscript denotes the RF channel index (1 or 2). The corresponding outputs of the cell exchange block are

$$\mathbf{g}_i^{(0)} \triangleq \begin{bmatrix} g_{2i,1} \\ g_{2i,2} \end{bmatrix}, \quad \mathbf{g}_i^{(1)} \triangleq \begin{bmatrix} g_{2i+1,1} \\ g_{2i+1,2} \end{bmatrix}. \tag{4}$$

Define the exchange matrix

$$\mathbf{P}(i) = \begin{cases} \mathbf{I}_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} & \text{if } i \text{ is even} \\ \mathbf{J} \triangleq \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} & \text{if } i \text{ is odd,} \end{cases} \tag{5}$$

so that

$$\mathbf{g}_i^{(0)} = \mathbf{P}(i)\, \boldsymbol{s}_i^{(0)}, \quad \mathbf{g}_i^{(1)} = \mathbf{P}(i)\, \boldsymbol{s}_i^{(1)}. \tag{6}$$

Here, $(s_{2i,1}, s_{2i+1,1})$ and $(s_{2i,2}, s_{2i+1,2})$ are the input cells associated with RF channel #1 and RF channel #2, respectively, on the given Polarization path; are the corresponding output cells

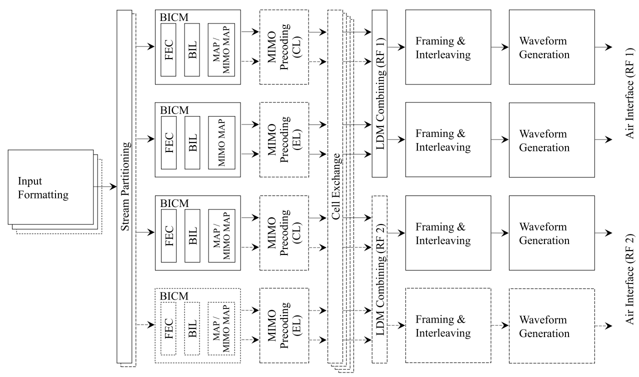

Fig. 15. Channel-bonded MIMO with Layered MIMO. Solid lines denote blocks common to all configurations, while dashed lines indicate blocks that can be disabled depending on configurations related to LDM, MIMO, and CB. Solid arrows represent signal flows common to all configurations, whereas dashed arrows denote optional signal flows that may be absent depending on the configuration.

to RF #1 and RF #2 after exchange. The output cells $g_{2i,1}$, $g_{2i,2}$, $g_{2i+1,1}$, $g_{2i+1,2}$ are then forwarded to their respective TI blocks on each path.

C. Joint Operation of LDM, CB, and MIMO

Fig. 14 depicts the extended architecture with Layered MIMO. For a channel-bonded PLP, all engaged data packets pass through a single input-formatting block and use the same **L1D_plp_id** on both associated RF channels. The BBPs generated for that channel-bonded PLP are split into two parallel streams at the stream partitioning block. Non-CB BBPs bypass stream partitioning.

Plain CB and SNR-averaging CB are both supported with Layered MIMO. Whenever SNR averaging is enabled, the two bonded streams originating from the same input-formatting block shall reside in the same LDM layer.

When enabled, cell exchange operates on cells after the MIMO precoding stage (for MIMO PLPs) and after the BICM stage (for SISO PLPs). The cell exchange procedure in Section VI-B, incorporating (3)-(6), is applied to the MIMO PLP's and SISO PLP's cells, respectively. The outputs of the cell exchange blocks then undergo LDM combining per Polarization, i.e., core and enhanced layer cells belonging to the same Polarization.

If a channel-bonded PLP with SNR averaging is present, Layered MIMO configurations must be identical across the bonded RF channels for the corresponding subframes: Layered MIMO type, injection level, and MIMO parameters must match. Other constraints in Section VI-A likewise apply whenever SNR averaging is used.

With plain CB, bonding is not restricted to homogeneous PLP pairs. A channel-bonded PLP may comprise a SISO PLP and a MIMO PLP, and part of a Layered MIMO subframe may be bonded with one not using Layered MIMO.

D. SISO CB With LDM

Not only for MIMO, progress has also been made for the SISO version of CB to incorporate LDM. Thus, TDM, LDM, FDM, and their combinations are all available to multiplex CB-involved PLPs with other PLPs. Channel-bonded PLPs can be multiplexed with non-CB PLPs.

By replacing all MIMO MAP blocks with MAP and removing MIMO precoders in Fig. 15, we get the SISO-only CB+LDM architecture. As also intended in the channel-bonded MIMO design, i.e., Fig. 15, cell exchange precedes LDM combining, so the decision to apply CB to the core and enhanced PLPs can be made independently.

When SNR averaging is enabled, again, the two mutually bonded PLPs should be configured identically, including their layer indices; i.e., only CL-to-CL and EL-to-EL bonding are allowed.

VII. Time Interleaving Memory Under Coexistence Scenarios

TI is one of the aspects that PHY scalability is cautiously addressed. As TI consumes dedicated buffer storage, receiver capability is bounded by available memory. The specification therefore binds permitted TI configurations to standard memory capacity at the receiver.

ATSC 3.0 defines TI memory sizes on a CDP basis. Here, *TI memory size* denotes the buffer consumption associated with a given TI configuration, measured in *cells*. The baseline constraint is $M_{\mathrm{TI},0} = 2^{19}$ cells, which manufacturers shall implement as the time de-interleaver memory for non-CB SISO capability. Collecting the descriptions in [58] and [60], the rule applying to non-CB SISO instances can be written as:

Rule 0 (TI memory size for non-CB SISO): Let $\mathcal{P}_{\mathrm{o}}$ denote the set of PLPs comprising a CDP, all non-CB and SISO. If convolutional TI (CTI) is used, let D_i be the CTI depth PLP $i \in \mathcal{P}_{\mathrm{o}}$ indicated by **L1D_plp_CTI_depth** in conjunction with **L1D_plp_TI_extended_interleaving**. The effective TI memory per PLP is $Q_i = \frac{1}{2}D_i(D_i - 1)$. Then the memory budget must satisfy:

$$\sum_{i \in \mathcal{P}_{\mathrm{o}}} \alpha_i Q_i \leq M_{\mathrm{TI},0}, \tag{7}$$

where $\alpha_i = 1$ for regular TI; $\alpha_i = \frac{1}{2}$ holds when the extended TI option is used. For hybrid TI (HTI), the same accounting applies: The sum of the effective memory required for regular-TI PLPs plus half the sum for extended-TI PLPs must not exceed $M_{\mathrm{TI},0}$. We abbreviate this rule as $\mathcal{R}_{\mathrm{TI}}(0)$. ∎

Basically, the maximum size of TI memory scales linearly with the number of TI processing blocks involved. ATSC 3.0 specifies identical TI modules per Polarization for MIMO. Accordingly, the baseline MIMO description in **A/322:2024-04** stated: *The memory requirement for SISO applies per Polarization, so MIMO requires twice the TI memory of SISO*. Formally, when $\hat{Q}_i$ denotes the effective TI memory usage per PLP extended to embrace MIMO PLPs and channel-bonded PLPs, $\hat{Q}_i = 2Q_i$ holds for MIMO PLPs and $\hat{Q}_i = Q_i$ holds for SISO PLPs.

However, that early statement overlooked possibility of CDPs containing both SISO and MIMO PLPs. Note that a CDP can also be a subset of another CDP at the same time. In the receiver capability context, SISO-only receivers may be implemented with SISO TI memory requirement only; SISO-modulated content should remain decodable by SISO-only receivers, PHY scalability derives the following:

Rule 1 (TI memory size for SISO-MIMO coexistence), $\mathcal{R}_{\mathrm{TI}}(\mathcal{M})$: When SISO and MIMO PLPs assemble a CDP, the total TI memory required for this CDP is twice the amount specified by $\mathcal{R}_{\mathrm{TI}}(0)$. Simultaneously, the subset comprising all SISO PLPs within this CDP, on its own, satisfies $\mathcal{R}_{\mathrm{TI}}(0)$.

More precisely, let $\mathcal{P}_{\mathcal{U}}$ be the universal set of all PLPs comprising a CDP, regardless whether each is SISO or MIMO; and let $\mathcal{P}_{\mathcal{S}} \subseteq \mathcal{P}_{\mathcal{U}}$ be the subset comprising all SISO PLPs within this CDP. Then, selection of $\{\hat{Q}_i\}$ shall satisfy

$$\sum_{i \in \mathcal{P}_{\mathrm{U}}} \alpha_i \hat{Q}_i \leq \mathcal{M}_{\mathrm{TI},M} \triangleq 2M_{\mathrm{TI},0} \tag{8a}$$

and

$$\sum_{i \in \mathcal{P}_{\mathcal{S}}} \alpha_i \hat{Q}_i \leq M_{\mathrm{TI},0} \tag{8b}$$

simultaneously. ■

By (8b), $\mathcal{R}_{\mathrm{TI}}(\mathcal{M})$ protects SISO receivers from $\hat{Q}_{i \in \mathcal{P}_{\mathrm{S}}}$ overruns exceeding legacy SISO receiver capacity $M_{\mathrm{TI},0}$, where a violation could occur if one enforced only (8a). Note that $\mathcal{R}_{\mathrm{TI}}(\mathcal{M})$ addresses non-CB scenarios.

Meantime, Extended TI is prohibited whenever MIMO precoding is enabled because of memory constraints.

This principle carries over to Layered MIMO scenarios. In line with the ATSC 3.0 LDM principle [77], both Layered MIMO Types A and B define TI mode for core PLPs; the enhanced PLPs follow the same TI as their associated core PLPs. Because TI is applied to LDM-combined cells, Layered MIMO faces the same TI condition as baseline MIMO: TI memory usage doubles relative to SISO. However, for Layered MIMO Type B, where SISO and MIMO necessarily coexist, issues behind $\mathcal{R}_{\mathrm{TI}}(\mathcal{M})$ always arise.

With Layered MIMO, $\mathcal{R}_{\mathrm{TI}}(\mathcal{M})$ generalizes to:

Rule 2 (TI memory size for Layered MIMO), $\mathcal{R}_{\mathrm{TI}}(\mathcal{LM})$: When combined PLP(s) using Layered MIMO form a CDP with other SISO or MIMO PLP(s) that do not use Layered MIMO, the total TI memory required for the CDP shall be twice the amount specified by $\mathcal{R}_{\mathrm{TI}}(0)$. Simultaneously, the subset comprising all SISO PLPs (including core PLPs in Layered MIMO Type B), within this CDP shall, on its own, satisfy $\mathcal{R}_{\mathrm{TI}}(0)$.

Formally, $\mathcal{R}_{\mathrm{TI}}(\mathcal{LM})$ mirrors $\mathcal{R}_{\mathrm{TI}}(\mathcal{M})$ and (8), with the clarification that Type B core PLPs are included in $\mathcal{P}_{\mathrm{S}}$. ■

Besides, Layered MIMO has no extended-TI exposure: Extended TI mode is prohibited for any Layered MIMO PLP, regardless of MIMO-precoding use. Plus, it should be noted in general LDM that there always exists a CDP including an enhanced PLP together with its associated core PLP(s).

CB also addresses the TI issues alike but tackles the problem in each RF channel:

Rule 3 (TI memory size for SISO CB), $\mathcal{R}_{\mathrm{TI}}(\mathcal{CB}_{\mathrm{S}})$: When channel-bonded and nonbonded PLPs assemble a CDP, while all involved PLPs use SISO, the total TI memory required for the CDP is twice the amount specified by $\mathcal{R}_{\mathrm{TI}}(0)$. Simultaneously, for each RF channel, the group of PLPs consisting of all nonbonded PLPs within this CDP shall satisfy $\mathcal{R}_{\mathrm{TI}}(0)$ on its own. ■

When any MIMO PLP is present in a CDP that includes both channel-bonded and nonbonded PLPs, the overall TI memory increases to four times the amount in $\mathcal{R}_{\mathrm{TI}}(0)$. This results from two independent doublings: Two Polarizations and their duplication over two RF paths. Note that, even when SISO+MIMO bonding is used, a single BBP stream is partitioned across both RF channels; therefore, no receiver will meaningfully decode only the SISO part within a bonded pair. As of this writing, commercial receivers implementing channel-bonded MIMO are not yet available; accordingly, the receiver capability profile for CB-MIMO targets the general MIMO+MIMO case rather than a SISO+MIMO special case. Hence, the design target TI memory for receivers supporting channel-bonded MIMO is $4\mathcal{M}_{\mathrm{TI},0}$ cells. Plus, when a MIMO PLP participates in a CDP that includes channel-bonded PLP(s), the per-RF constraints may be replaced by $\mathcal{R}_{\mathrm{TI}}(\mathcal{M})$ or $\mathcal{R}_{\mathrm{TI}}(\mathcal{LM})$ as applicable.

VIII. Delivered Product in Multiple PLPs: PHY Scalability Aspect

Another part in which PHY scalability underpins the design is allocation of link-layer and service signaling. In the ATSC 3.0 architecture, referring to A/330 [78] and A/331 [79] specifications, a receiver should initially acquire the requisite link- and delivery-layer information discover, locate, and access services carried by the physical layer. This information is conveyed via LLS, link mapping table (LMT), etc. comprehensively referred to as *IP-level signaling information* in Section V-A1 of A/327.

For an initial service scan, for example, the receiver should acquire LLS—in particular the service list table (SLT)—to discover services and the entry points to their service layer signaling (SLS). Without this procedure, the user cannot reliably retrieve the desired media service even if physical-layer decoding succeeds. Accordingly, the IP-level signaling is carried in at least one PLP within a CDP.

From this perspective, a physical-layer compatibility issue arises for the carriage of IP-level signaling. Consider a CDP containing both SISO and MIMO PLPs, while a SISO PLP subset forms another delivered product concurrently. For instance, a scalable video service may place the SVC base layer on a SISO PLP and the SVC enhancement layer on a MIMO PLP. In this case, the SISO PLP alone presents a lower resolution video service; and the MIMO PLP adds metadata and media that scale video quality when combined with the SISO base layer. Reasonably, in this scenario, the IP-level signaling must be conveyed over SISO signals so that SISO-only receivers can acquire service; otherwise, they will fail to obtain any service despite successfully decoding the intended SISO PLPs.

This concern motivates a general principle: The carriage of IP-level signaling must ensure compatibility with receivers that have the *least functional capability* in extensional technologies, e.g., Layered or non-layered MIMO and CB. In terms of PHY scalability (see Section IV), *receivers with lower PHY scalability are preferentially supported to maximize compatibility*.

Since this principle appears as essential to system operation, this and the below may need to be mirrored in related specifications, such as A/330 [78], A/331 [79], or else.

This principle combines with the robustness-driven rule previously existed, yielding the following rules. When a CDP mixes SISO and MIMO PLPs, the IP-level signaling should reside in the most robust SISO PLP among the PLPs carrying the CDP. When LDM or Layered MIMO is used, the CDP should carry the IP-level signaling in the most robust core PLP using SISO.

Likewise, when a CDP mixes channel-bonded PLPs and nonbonded PLPs, the CDP should carry the IP-level signaling in the most robust, nonbonded core PLP among the engaged PLPs within each RF channel. If nonbonded core PLP is absent, the IP-level signaling is included in the most robust core PLP using CB. Overall, a general rule that accounts for mixed use of SISO, MIMO, Layered MIMO, and CB is as follows: Within each RF channel, the IP-level signaling should be present in the most robust core PLP that is nonbonded and uses SISO. If no such nonbonded SISO core PLP exists, the IP-level signaling should be included in the most robust MIMO core PLP, applying the one with lower PHY scalability between MIMO and CB in the service area.

IX. TxID in MIMO Systems

The TxID feature is also extended as compatible with MIMO operation. TxID is a RF watermark technique used to identify transmitters and to radiograph per-transmitter multipath channel profiles. From this original purpose, TxID has been used for SFN construction/management and channel characterization campaigns [43]. In Brazil's TV 3.0 context, the SBTVD Forum and broadcasters additionally envision service-tracking use cases—particularly for GSL [32]—so MIMO-capable TxID was a practical requirement rather than a mere by-product of MIMO migration.

Among several design options, the simplest form is adopted: The TxID code and its injection level are assigned independently per Polarization, enabling identification not only for individual transmitter but also for Polarization. The predefined TxID signal generation and injection methods are reused on each Polarization. Correspondingly, the STLTP data structure is updated in A/324 to carry these per-Polarization fields as in Table VI.

X. Conclusion

This paper presented and proposed the system design and features that constitute *ATSC 3.0 MIMO Extension*. The scope was the physical layer and related aspects, covering the technologies newly codified in A/322, A/324, and A/327. We detailed the definition and baseline clarifications, processing and procedure descriptions, signaling parameters, and configuration constraints, together with the design rationale. In line with the investigation, the history of Brazil TV 3.0 and ATSC 3.0 standardization backdrops were elaborated.

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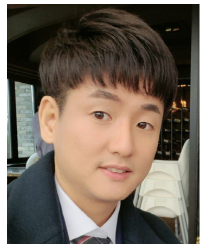

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